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Bone-Conduction Threshold Measurements: Effects of Occlusion, Enclosures, and Masking Devices

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I. EFFECTS OF OCCLUSION OF EAR CANALS ON BONE-CONDUCTION THRESHOLDS

BONE-conduction threshold measurements are affected markedly by changes in the physical condition of the listener's head. Of special importance are changes which affect the external ear canals. Many investigators have shown that, for a normal-hearing person, occlusion of both ear canals causes a shift of the bone-conduction threshold to lower intensities by as much as 25 db at low frequencies, such as 125 and 250 cycles, and by lesser amounts at frequencies up to at least 2000 cycles. This shift is illustrated in Fig. 1, which gives the curves for a single individual with normal hearing (NW). Curve 1 is for open ear canals, Curve 2 for ear canals occluded by paraffin-cotton plugs. The threshold is given in each case in terms of the effective amplitude of the vibrator button of the calibrated induction-type electrodynamic vibrator[1] shown in Fig. 2. The vibrator button (area 0.665 sq. cm) was applied at the center of the forehead, with a constant force of 370 grams-weight, by means of the apparatus shown in the photograph.

Most of the measurements in the following series of experiments were made with this apparatus, using an increased force of application of 412 g-wt. Care was taken to avoid all interference from stray air radiation.

Variation of the type of plugs used to occlude the ear canals yielded the data given in Table I. For the determination of these data, RG, with essentially normal hearing, acted as listener.

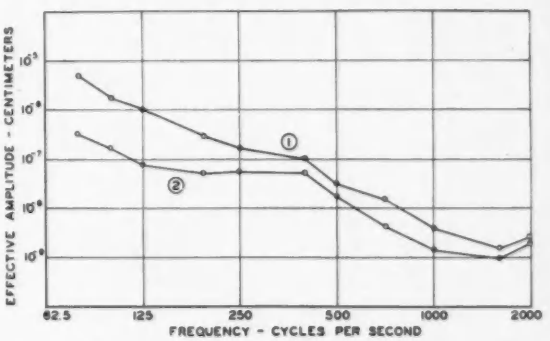

FIG. 1. Shift of the bone-conduction threshold curve by occlusion of the ear canals. Curve 1 is for open ear canals; Curve 2 is for occluded canals. (One observer, NW.)

[1] N. A. Watson, J. Acous. Soc. Am. **9**, 99–106 (October, 1937).

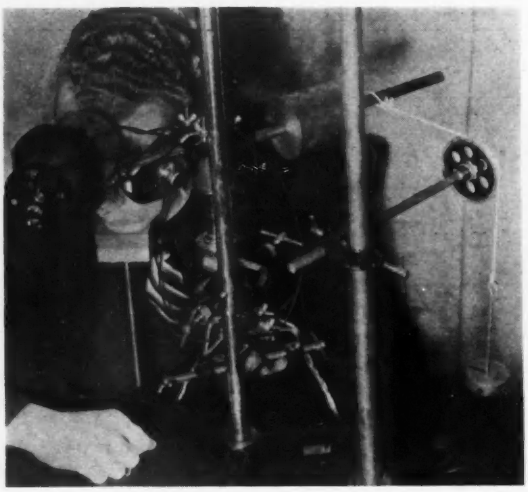

FIG. 2. Induction-type electrodynamic bone-conduction vibrator, mounting, and means of application of vibrator button to center of forehead.

Both ears were occluded in each instance. The frequency of the test tone was 250 cycles. When loose dry cotton plugs, each with a mass of only 0.1 g, were used, there was a bone-conduction threshold shift of 10 db to lower intensities although the occlusion was very poor and the rise in air-conduction threshold owing to the cotton was only 2.5 db. Vaseline and cotton plugs, with six times the mass, somewhat better occlusion, and four times as many db air-conduction insulation, gave a bone-conduction threshold shift only 3.5 db more than the loose cotton. Rubber swimming ear stops, with the same mass each as the vaseline and cotton plugs, but with *complete occlusion*, gave an air-conduction insulation of 25 db (ten times the number of db for the loose cotton and two and a half times the number for the vaseline and cotton) and a bone-conduction shift of −24 db, which is almost equal in magnitude but opposite in direction to the air-conduction shift. Paraffin-covered cotton plugs, softened and moulded to the canals to give complete occlusion, were two grams each in mass, three and a third times that of the rubber swimming ear stops, and yet the air-conduction insulation and bone-conduction threshold lowering were almost identical with those for the swimming ear stops. Rubber ear defenders developed by V. O. Knudsen[2] were specially adapted for this test by partially filling them with mercury, closing the ends with fiber inserts, and sealing them in the ear canals with vaseline. Thus adapted, the mass of each was two grams and the closure complete. The air-conduction insulation, 35 db, was 10 db more than for the paraffin-covered cotton plugs, yet the bone-conduction threshold lowering was the same, 24 db.

These data indicate: (1) that complete occlusion is *not* necessary to produce *some* bone-conduction threshold shift at 250 cycles, but that *complete* occlusion is necessary to produce a *maximum* shift at that frequency; (2) that if closure is complete, variation of the mass of the occluding plug does not give a corresponding variation of the bone-conduction threshold shift, the shift sometimes even remaining constant; and (3) that the bone-conduction threshold shift for completely occluding plugs of equal mass is not correlated with the air-conduction insulation, which increased greatly in the case tested, while the bone threshold shift remained practically unchanged.

II. EFFECTS OF PLACING ENCLOSURES OVER THE EARS

Since a bone-threshold shift is produced by occluding the ear canals and thus forming small

[2] "Ear Defenders," National Safety News (February, 1939).

TABLE I. Bone- and air-conduction threshold shifts owing to various types and degrees of occlusion of an observer's ear canals. Observer: RG (normal hearing). Frequency: 250 cycles. Electrodynamic bone vibrator at center of forehead. Both ears occluded by plugs.

Type of plug	Mass of each plug in grams	Degree of occlusion	AC threshold shift—db	BC threshold shift—db
Loose dry cotton	0.1	Very poor	2.5	−10
Vaseline and cotton	0.6	Fair	10	−13.5
Swimming ear stops (rubber)	0.6	Complete	25	−24
Paraffin-covered cotton—molded to ear canal	2.0	Complete	25	−24
Rubber ear defender: Hg-filled—fiber insert—vaseline seal	2.0	Complete	35	−24

TABLE II. Bone-conduction threshold shifts owing to various types of enclosures placed over the ears of an observer—exactly similar enclosures over left and right ears. Observer: RG. Electrodynamic bone vibrator at center of forehead.

Type of enclosures	Volume of each enclosure—cc	Method of support of enclosures	Frequency—cycles per second	BC threshold shift—db
Brush type A headphones; sponge rubber ear cushions	8	Regular headband and spring arc	125	−12
			250	−22.5
			500	−18
			1000	− 7.5
			2000	− 1.5
Pint jars, empty; sponge rubber rings	500	Regular headband, elastic supports	250	− 6
Pint jars, each lined with 8 grams cotton batting, 1 cm thick; sponge rubber rings	500 (less vol. of cotton)	Regular headband, elastic supports	250	− 3
Pint jars, each filled with 14 grams cotton batting, 1 cm thick; sponge rubber rings	500 (less vol. of cotton)	Regular headband, elastic supports	250	− 3
Quart jars, empty; sponge rubber rings	1000	Regular headband, jars suspended by strings	125	− 7.5
			250	0
			500	0
Quart jars each lined with 8 grams cotton batting, 1 cm thick; sponge rubber rings	1000 (less vol. of cotton)	Regular headband, jars suspended by strings	125	− 6
			1000	0
Wooden boxes of ¾ in. pine, lined with cotton batting, 1 cm thick	6700	Wooden support stands; extensions; clamps	128	None at any frequency for either RG or NW with Son. Aud. Model 1 bone vibrator
			256	
			512	
			1024	
			2048	
			4096	
			8192	

TABLE III. Bone-conduction threshold shifts owing to various types of enclosure placed over one ear of an observer. Observer: RG. Electrodynamic bone vibrator at center of forehead.

Type of enclosure	Volume of enclosure —cc	Method of support of enclosure	Enclosure over	Frequency—cycles per second	BC threshold shift—db
WE electrodynamic earphone with sponge rubber ear cushion	12	Standard headband	Left ear	125	−15
				250	−16.5
				500	−15
				1000	− 6
				2000	0
			Right ear	500	−15
				1000	− 6
Quart jar, empty; sponge rubber ring	1000	Ringstand; rod; clamp	Right ear	125	− 4.5
Wooden box of ¾ in. pine, lined with cotton batting, 1 cm thick; sponge rubber ring	6700	Wooden support stand; extension clamp	Right ear	125	0
				250	0

closed volumes with the ear drums as the inner walls of the volumes, one would expect that the placing of any small enclosures *over* the ears and pressing them against the ears or the adjacent portions of the head, thereby forming chambers consisting partly of the external ear canals and thus closed at the inner ends by the ear drums, would produce a bone-threshold shift similar to that produced by occlusion with ear plugs. Certain anomalous results, which arise when

bone-conduction tests are made on one ear, with a masking noise introduced into the listener's other ear by means of an earphone, led the authors to suspect that a masking earphone *does* cause such a bone-threshold shift. Thus an investigation was made of bone-conduction thresholds when enclosures of various sizes and types were placed over the ears.

The first set of experiments was made with exactly similar enclosures over both ears. Results for various enclosures are given in Table II. A typical arrangement of apparatus (500 cc enclosures) is shown in Fig. 3. These data indicate that enclosures of 1000 cc in volume or less produce a shift at some or all frequencies for some observers. Rigid, sealed, wooden boxes of rectangular shape, and approximately 6700 cc in volume, lined with cotton batting approximately 1 cm thick, do not give the shift for the normal-hearing observers tested, for frequencies down to 125 cycles.

A similar, but somewhat smaller, effect arises when only one ear is covered. (This is the situation when a masking earphone is used.) The magnitude of the effect is indicated in Table III for different types of enclosures and conditions of their use. In all instances, the vibrator was applied at the center of the forehead with the force the same as when both ears were covered. The bone-threshold shift amounted to as much as -16.5 db at some frequencies for a single earphone and sponge rubber cushion. The quart jar was not large enough to eliminate the shift at all frequencies for all observers even when the jar was lined with absorptive material (cotton batting approximately 1 cm thick). The effect disappeared for all test frequencies down to 125 cycles when the large wooden boxes (6700 cc) with walls lined with cotton batting approximately 1 cm thick were used.

FIG. 3. Arrangement of bone-conduction vibrator and 500-cc enclosures for testing the effect of enclosures on bone-conduction thresholds. (Photograph through the courtesy of John Brenneis and *The California Monthly*.)

To determine the critical volume for each frequency, i.e., the smallest volume not causing a bone-threshold shift for that frequency, a variable-volume cylindrical enclosure with a tight-sealing piston at the far end was used. The cylinder was of steel tubing, 6 inches in outside diameter and $\frac{3}{32}$ inch in thickness. The piston at the far end was made of $\frac{3}{4}$-inch wood. It was provided with rubber cord around its circumference to give a tight fit. The listening end of the tube was closed by a $\frac{5}{32}$-inch brass plate, in the center of which was a $1\frac{1}{2}$-inch hole, just large enough to admit the ear. Fastened to the brass plate was a soft sponge rubber pad $\frac{5}{8}$ inch thick with a hole in the center the same size as that in the brass plate. The pad served as an acoustical seal against the head around the ear. Measurements were made with two normal-hearing listeners for volumes ranging from 100 cc to 4000 cc for frequencies of 128, 256, and 512 cycles. These measurements indicated critical volumes of approximately 1500 cc, 1000 cc, and 150 cc, respectively, for these frequencies.

A tentative explanation for the threshold shift is as follows: When the ear canals are occluded, there is a pressure fluctuation, or acoustic pressure, set up in the resultant small volumes because of the vibrations of the bony portions of the canal walls. This acoustic pressure acts on the ear drum similarly to that of a sound from the diaphragm of a telephone receiver and activates the inner ear by air conduction. This is in addition to the direct bone transmission. The two

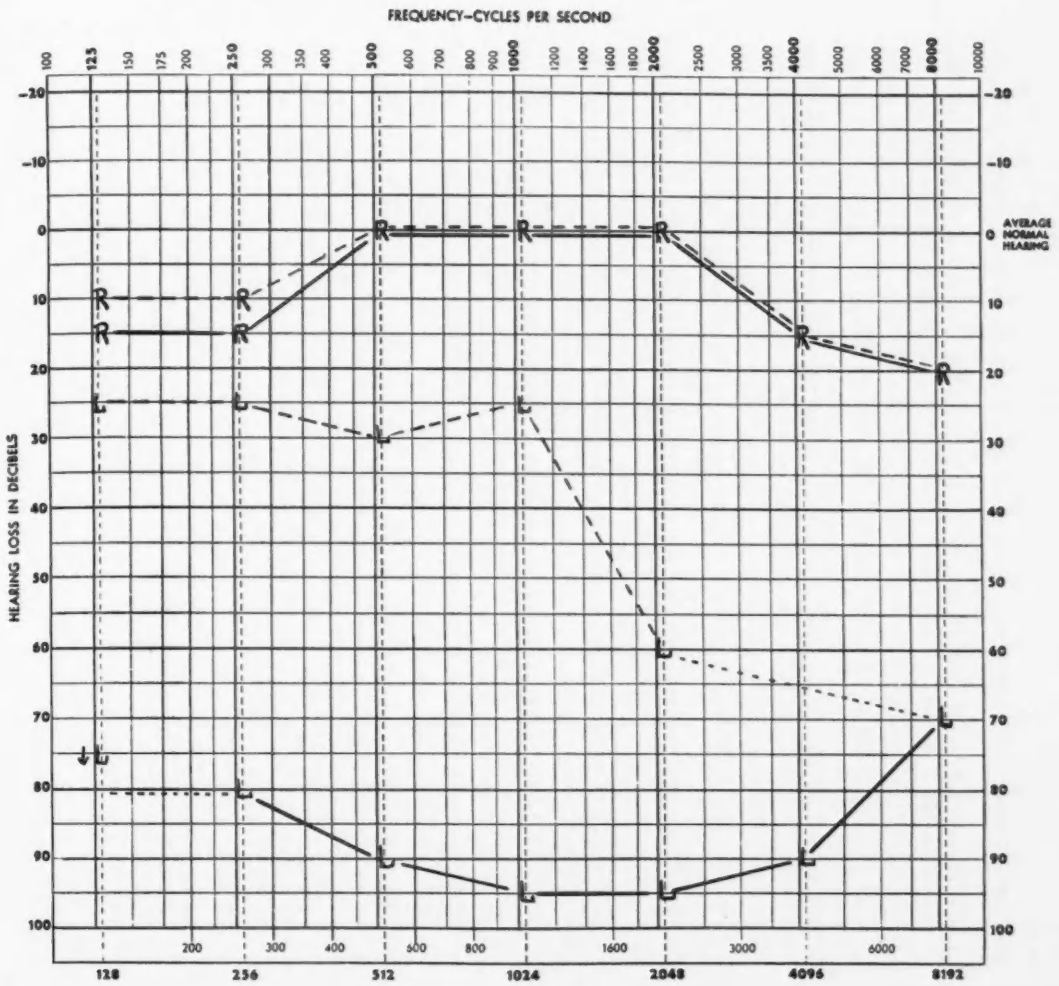

FIG. 4. Air- (—) and bone-conduction (- - -) threshold curves for observer RO. The bone-threshold curve for the left ear was taken in accordance with the best procedure, as given in Part III of this paper. Although no bone-conduction response was obtained at frequencies above 2000 cycles, the bone-conduction curve was extrapolated to give equal air- and bone-conduction losses at 8000 cycles.

methods of transmission eventually act at least partially in phase in the inner ear to produce a greater stimulation than the direct bone transmission alone. Thus both, acting together, produce threshold stimulation at a smaller amplitude of vibration of the bone vibrator than when the canals are open and the vibrations of the canal walls do not produce an acoustical pressure in the ear canals sufficient to provide appreciable stimulation, so that the direct bone transmission is the only effective mode of transmission. This difference in amplitude measures the threshold shift.

When small enclosures are placed over the ears, they combine with the ear canals to encompass volumes of air in which acoustic pressures are produced by the vibration of the ear canal walls; but the acoustic pressures developed are smaller than in the case of occluded canals. As the size of the enclosures is made larger and larger, the acoustic pressures set up by the vibrating canal walls become smaller and smaller, and the threshold shift also diminishes, until at the critical volumes the acoustic pressures become negligible, the direct bone transmission is the only effective mode of transmission, and the threshold shift disappears.*

* The explanations for these effects, in terms of the acoustical elements and "circuits," as well as more detailed experiments verifying them, were being investigated by the

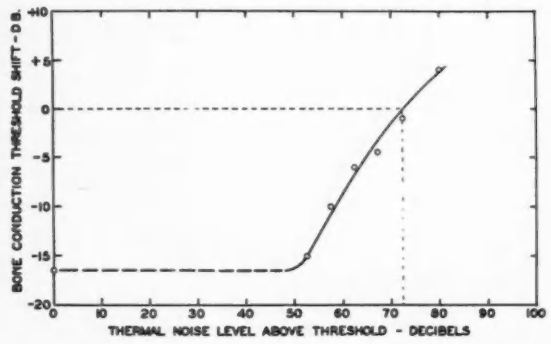

FIG. 5. Effect of masking earphone and thermal noise masking sound on the bone-conduction threshold of observer RG for the frequency 250 cycles. The thermal noise level above threshold required just to counteract the threshold shift owing to the masking phone is indicated by the vertical dashed line.

On the basis of this tentative explanation, one would expect no bone-threshold shift if the external canal of the poorer ear of a person with unilateral conductive loss were occluded, and a marked shift if the external canal of the nearly normal ear were occluded. This was checked with observer RO, whose air- and bone-threshold curves appear in Fig. 4. A wax-filled plug was used: mass, 8 g; closure, fair. The test frequency was 250 cycles. The electrodynamic vibrator was placed at the center of the forehead. When the poorer ear was occluded, there was no appreciable bone-threshold shift; but when the better ear was occluded, there was a −21-db shift, which checks the expectations. Furthermore there was no bone-threshold shift when a small enclosure was placed over the poorer ear, but a definite shift when a small enclosure was placed over the better ear. However, there was no shift when the large wooden box (6700 cc) was placed over the better ear.

III. EFFECTS OF MASKING DEVICES

An earphone, with a sponge rubber ear cushion to prevent stray air radiation, has been used by some investigators to introduce thermal masking noise into one ear while testing the bone-conduction acuity of the other. The effect of such an earphone and cushion (without masking sound) when the bone vibrator is placed at the center of the forehead has been discussed above.

junior author (R. S. Gales) at the time he was called to War Research and will be published later.

To determine the effect when a masking noise is used the following experiment was performed with RG as listener: the electrodynamic bone vibrator was used as the source and was applied at the center of the forehead. The test frequency was 250 cycles. Thermal noise was used for masking; it had the same intensity for each 5-cycle band over the range 20–15,000 cycles. The masking phone was placed over the listener's right ear. The results are given by the curve in Fig. 5, in which the abscissae are levels above threshold for thermal noise, and the ordinates are bone-threshold shifts from the open canal bone-conduction threshold. For no masking noise, the 250-cycle bone-threshold shift from the open canal threshold was −16.5 db. The thermal noise did not affect this shift until its level was about 50 db above threshold. Further increase of the thermal noise level brought the bone threshold higher and higher, until the shift was counteracted and the bone threshold returned to the open canal value at a thermal noise level of 72.5 db above the thermal noise threshold. Still further increases of noise level shifted the localization of the test tone to the opposite ear and raised the threshold above the open canal value.

Similar effects occurred at lower and higher frequencies, other conditions remaining the same. The results are listed in Table IV. In the second column are given the bone-threshold shifts from the open canal values for the frequencies listed—shifts caused by placing the earphone and cushion over the ear. In the third column are the thermal noise levels above thermal noise threshold required to counteract the bone-threshold shift

TABLE IV. Bone-conduction threshold shifts owing to an earphone over an observer's ear; also corresponding levels of thermal masking noise above its threshold required to return the bone threshold to its "open canal" value. Observer: RG. Electrodynamic bone vibrator at center of forehead. Earphone: WE electrodynamic with sponge rubber ear cushion. Left ear covered by earphone and cushion.

Frequency—cycles per second	BC threshold shift—db	Level of thermal masking noise (in db above its threshold) required to return bone threshold to open canal value
125	−13.5	85
250	−16.5	72.5
500	−15	55
1000	− 6	55

caused by the presence of the earphone. At all of the frequencies tested, a thermal noise louder than that just counteracting the bone-threshold shift caused a shift of localization of the test tone to the unmasked ear and a rise in the bone threshold above the open canal value.

When the bone vibrator was placed on the mastoid corresponding to the ear to be tested and opposite to the ear with the masking phone, bone-threshold shifts toward lower intensities occurred much as when the vibrator was at the center of the forehead. In most cases the masking earphone also produced the localization in the ear which was covered, making it seem as if the test tone were actually coming from the receiver on the covered ear, rather than from the bone vibrator on the opposite mastoid.

The same earphone without a rubber ear cushion also produced shifts, different in magnitude at the various frequencies, and entirely absent at some of them. This effect, in which the earphone is not acoustically sealed to the head, is more complicated than that which arises when a small enclosure is placed over the ear.

An example of the bone-threshold shifts for the bone vibrator on the mastoid, and the earphone, with or without a cushion, held over the opposite ear, is given in Table V. For these thresholds the Sonotone Model 1 audiometer, with its bone vibrator specially designed to eliminate air radiation,[3] was used. The vibrator was placed on the left mastoid of NW and a Western Electric dynamic earphone with sponge rubber ear cushion was placed on the right ear. The shift was approximately 10 db toward lower intensities over the frequency range 128–1024 cycles and 5 db at 2048 cycles. (The audiometer is calibrated in 5-db steps.) When the ear cushion was removed and the phone used alone, the shift disappeared at the lower frequencies, but was greater at 1000 cycles.

Thus it is evident that a phone with or without an ear cushion is unsuitable for a thermal noise masking device. To counteract the threshold shift and bring the threshold back to the open canal value, it would be necessary to introduce a thermal masking noise of high intensity into the ear covered by the air-conduction earphone, much as in the case in which the vibrator was at the center of the forehead. Thus the use of a moderate amount of thermal masking noise would give a spurious bone threshold for the ear tested.

The absence of a bone-threshold shift when a single enclosure of larger than the critical volume was used, suggested as a better masking device a large enclosure with the air-conduction phone at the far end and a hole for the ear at the near end.

TABLE V. Bone-conduction threshold shifts owing to an earphone over one ear of an observer; bone vibrator on opposite mastoid. Observer: NW. Sonotone Model 1 Audiometer bone vibrator applied to the left mastoid. WE electrodynamic earphone held over the right ear by the right side of a regular two-earphone headband. (Volume of enclosure approximately 12 cc.)

Frequency—cycles per second	Bone conduction threshold shift—db: Earphone with sponge rubber ear cushion	Bone conduction threshold shift—db: Earphone alone
128	−10	0
256	−10	0
512	−10	− 5
1024	−10	−20
2048	− 5	− 5
4096	0	0
8192	0	0

Such a box was built and tested. The volume was approximately 6700 cc, and the interior was lined with cotton batting. There were no appreciable bone-threshold shifts for any frequency down to 100 cycles for either of the authors, and the masking was readily effected by the sound from the source at the far end of the box. Thus the padded box appears to be a satisfactory masking device, but is heavy and clumsy. On the basis of the critical volume data given above, an enclosure of 2000-cc volume would be large enough for tests with frequencies down to approximately 100 cycles.

Tests have also been made on a few hard-of-hearing persons, especially those with marked unilateral losses. It is in such cases that the correct masking is absolutely necessary for determining an accurate bone-conduction threshold for the poorer-hearing ear. If no masking is used, the threshold for the poorer-hearing ear is not determined at all; the vibrations elicit a response in the better-hearing ear, although the vibrator is on the side of the poorer-hearing ear. When an earphone with a sponge rubber ear cushion is

[3] V. O. Knudsen and I. H. Jones, Laryngoscope **46**, 523 (1936).

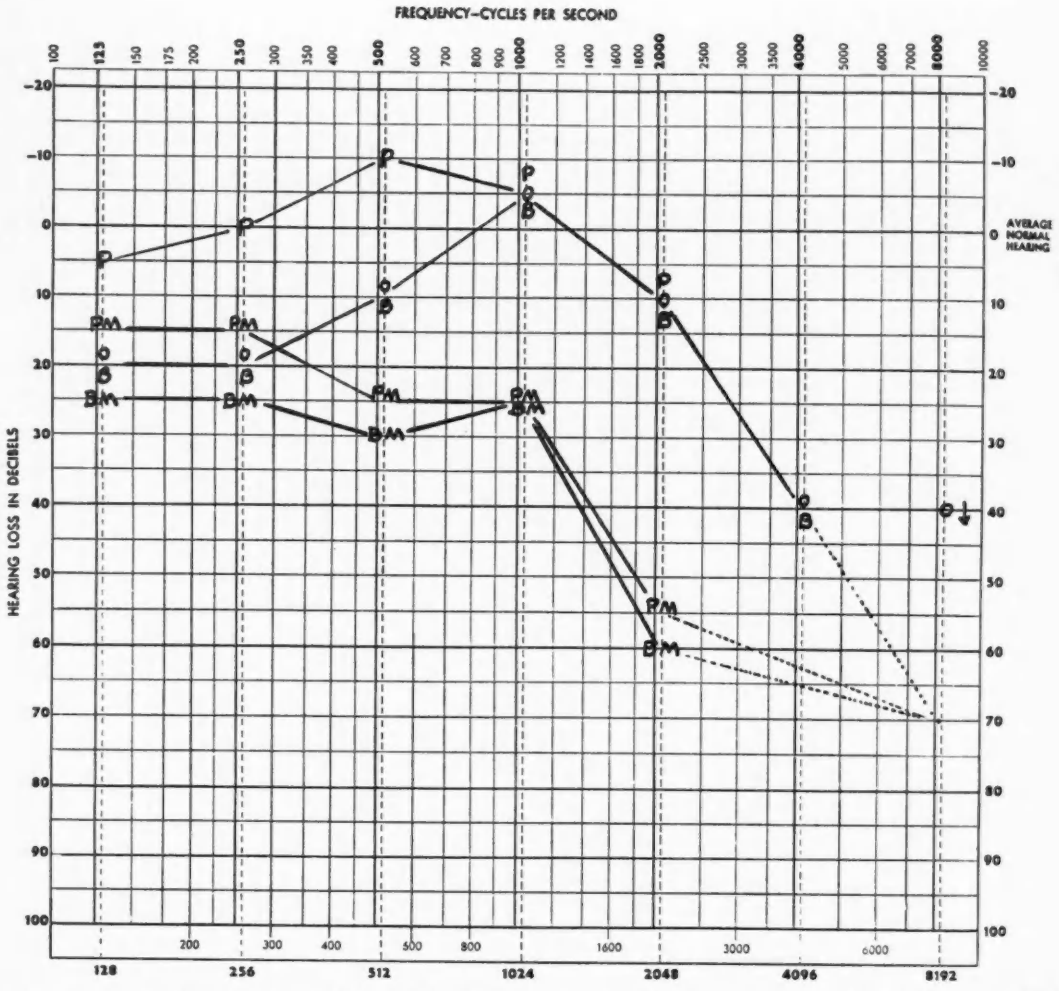

FIG. 6. Bone-conduction threshold curves for the poorer-hearing left ear of observer RO. The loss at 8000 cycles was estimated on the basis of the corresponding air-conduction loss. O—open canal; P—left ear covered by WE earphone and sponge rubber; B—left ear covered by wooden masking box; PM—same as P except thermal masking noise used; BM—same as B except thermal masking noise used.

placed on the better ear it sometimes causes a bone-threshold shift and gives an even more inaccurate bone-threshold curve for the poorer ear. When moderate amounts of thermal masking noise are introduced by this phone the bone threshold is still incorrect. The large masking box, however, gave no threshold shifts in the cases tested and yet allowed the introduction of thermal noise to mask the better ear and give a true bone threshold.

An example of these effects for an observer with unilateral, predominantly conductive loss follows: the air-conduction threshold curves for the observer (RO) were shown in Fig. 4, with the best bone-conduction curves obtainable. The bone-threshold curves for the poorer ear, determined under various conditions, are shown in Fig. 6. At all frequencies which could be tested, the bone thresholds with the masking box over the better ear (indicated by *B* points) were the same as the thresholds with open canals (indicated by *O* points), whereas the thresholds with the earphone and cushion over the better ear (indicated by *P* points) were at much smaller intensities at frequencies of 128, 256 and 512 cycles, indicating smaller loss, but wrongly so. Thus the masking box introduced no additional inaccuracies, while the phone and cushion did. When moderate thermal masking noise was introduced by means of the masking phone, the threshold (indicated by PM points) still lay at levels less (and therefore more inaccurate) than

the open canal values for the frequencies 128 and 256 cycles. When an equivalent amount of thermal masking noise was introduced into the better ear by means of the masking box, the bone-conduction threshold (indicated by BM points) lay at intensities greater than the open canal thresholds. This is probably the correct bone threshold; at least it is more nearly correct than those with open canals or with masking by a thermal noise introduced by an earphone.

IV. SUMMARY

Bone-conduction threshold shifts are produced by occlusion of external ear canals with plugs. They are also produced by covering the ears with enclosures having volumes smaller than the critical values (which vary with frequency). Similar, but smaller, effects are produced by occlusion of one ear canal or by covering one ear. The use of a masking phone over the better ear of an observer while testing the bone acuity of the poorer ear often results in a spurious bone threshold. A better device, adequate for bone-conduction testing at frequencies down to 100 cycles, is a masking box, with earphone at the opposite end from the ear, and with a volume greater than the critical volumes for all test frequencies.

Filtered Thermal Noise—Fluctuation of Energy as a Function of Interval Length

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(Received February 10, 1943)

Let a source of thermal noise be connected to the input of a band pass filter. Consider the energy which would be dissipated during the interval t_1 to t_1+T if the output current were to flow through a resistance of one ohm. When T is held fixed and t_1 regarded as a random variable, the resulting energies have a distribution whose average and standard deviation depend upon T. Here this dependence is studied. The standard deviation of the difference of the energies of two contiguous intervals, each of length T, is also obtained.

1. INTRODUCTION

SUPPOSE the input of a filter to be connected to a source of thermal noise and the output current to flow through a resistance of one ohm. Let $I(t)$ be the output current. Since it flows through a resistance of one ohm the energy it dissipates in the interval (t_1, t_1+T) is

$$E(t_1, T)=E=\int_{t_1}^{t_1+T} I^2(t)dt. \tag{1.1}$$

If the starting point t_1 of the interval be regarded as chosen at random, then E is a random variable. It has a certain distribution, a mean value m_T, and a standard deviation σ_T, all of which depend upon T.

Here we derive formulas for m_T and σ_T. We are also interested in the standard deviation $\sigma_{S,T}$ of the difference between two E's whose starting points are separated by a time S. Thus, we want the standard deviation of the quantity

$$E(t_1, T)-E(t_1+S, T)=\int_{t_1}^{t_1+T} I^2(t)dt-\int_{t_1+S}^{t_1+S+T} I^2(t)dt \tag{1.2}$$

where t_1 is chosen at random.

The principal results of our studies are shown by the curves of Fig. 1 in which the following are plotted:

(1) $y_A=\sigma_T/m_T$ *versus* $T(f_b-f_a)$ for an ideal band pass filter for the case $f_a \gg f_b-f_a$ where f_b and f_a are the highest and lowest transmitted frequencies.

(2) $y_B=\sigma_T/m_T$ *versus* $T(f_b-f_a)_{\text{equivalent}}$ for a filter whose band pass characteristic varies like $\exp[-c(f-f_0)^2]$ where f_0 is the mid-band frequency. The subscript "equivalent" indicates that m_T for the filter is the same as the m_T for an ideal filter with the pass band f_b-f_a. It is assumed that $f_0 \gg (f_b-f_a)_{\text{equivalent}}$.

(3) $y_C=\sigma_{T,T}/m_T$ *versus* $T(f_b-f_a)$ for the ideal band pass filter associated with y_A. In this case one interval of length T starts when the other stops.

In deriving these results, the noise current is represented as the sum of sinusoidal components all having the same amplitude but with random phase angles. This representation is stated in Section 2 and is discussed in the Appendix. In Sections 3 and 4 it is applied to the determination of m_T and σ_T, respectively.

The value of m_T is proportional to T and is given by Eq. (3.2). The expression for σ_T^2 is more complicated and is given in (4.14) as a double integral. In Section 5 a similar expression is derived for $\sigma_{S,T}^2$. The evaluation of the integrals for m_T and σ_T^2 in the case of a band pass filter is taken up in Section 6, and the integral for $\sigma_{S,T}^2$ is evaluated in Section 7. In Section 8 integrals for m_T and σ_T^2 are evaluated for the case in which the band pass filter has a normal law characteristic.

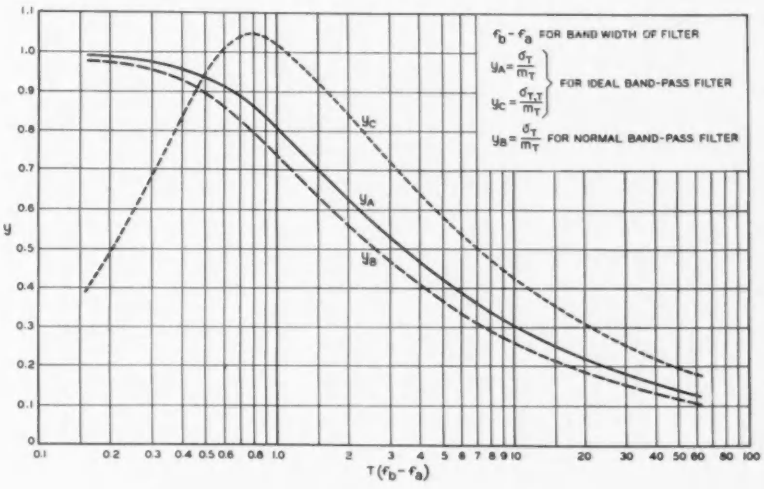

FIG. 1.

Instead of considering the energy, i.e., the integral of $I^2(t)$, we may consider the charge which flows past some point in the circuit. Some discussion of this problem is given in Section 9.

I wish to acknowledge, and to express my appreciation for the help which I have received from my associates in the preparation of this paper.

2. REPRESENTATION OF CURRENT

Let $A(f)$ be the ratio of the output current to the input current of the filter when a steady sinusoidal voltage of frequency f is applied to the input. Let $w(f)df$ be the average power dissipated in one ohm by those components of $I(t)$, the output current, which lie in the band $(f, f+df)$. If the thermal noise input be regarded as composed of many components which are of the same amplitude, but of random phase, and are distributed uniformly along the frequency scale, then $w(f)$ is proportional to $A^2(f)$.

$$w(f) = KA^2(f). \tag{2.1}$$

If W is the average power dissipated in the one ohm by $I(t)$

$$W = \lim_{T\to\infty} \frac{1}{T}\int_0^T I^2(t)dt = \int_0^\infty w(f)df = K\int_0^\infty A^2(f)df \tag{2.2}$$

which is an equation to determine K when W and $A(f)$ are given.

We assume that the statistical properties of the output current are the same as those of

$$I_N(t) = \sum_{n=0}^{N} C_n \cos(\omega_n t - \varphi_n) \tag{2.3}$$

where $\varphi_0, \varphi_1, \cdots \varphi_N$ are random angles and

$$\omega_n = 2\pi f_n, \quad f_n = n\Delta f, \quad C_n = [2w(f_n)\Delta f]^{\frac{1}{2}}. \tag{2.4}$$

Δf is the frequency difference between "adjacent" components and $w(f_n)\Delta f$ is the average power dissipated in the one ohm by the component of frequency f_n. After computing the statistical constants we let $\Delta f \to 0$ and $N \to \infty$ in such a way as to cover the entire frequency range. It seems to be difficult to give a really satisfactory justification of the representation (2.3). Some thoughts along this line are given in the Appendix.

Instead of using the definitions (1.1), (1.2) for $E(t_1, T)$ and the energy difference, our representation allows us to set

$$E(t_1, T)=E=\int_{-T/2}^{T/2} I_N^2(t)dt. \tag{2.5}$$

$$E(t_1, T)-E(t_1+S, T)=\int_{-(S+T)/2}^{(T-S)/2} I_N^2(t)dt-\int_{-(T-S)/2}^{(T+S)/2} I_N^2(t)dt \tag{2.6}$$

where t_1 has been set equal to $-T/2$ and $-(T+S)/2$, respectively. The randomness has gone out of t_1 into the phase angles $\varphi_0, \varphi_1, \cdots$.

3. THE MEAN VALUE m_T OF E

From (2.5)

$$E=\int_{-T/2}^{T/2} dt \sum_{n=0}^{N}\sum_{m=0}^{N} C_nC_m \cos(\omega_n t-\varphi_n)\cos(\omega_m t-\varphi_m). \tag{3.1}$$

When we average over all values of φ_n we get zero if $m\neq n$ and

$$\frac{1}{2\pi}\int_0^{2\pi}\cos^2(\omega_n t-\varphi_n)d\varphi_n=\tfrac{1}{2}$$

when $m=n$. Hence

$$\begin{aligned} m_T&=\int_{-T/2}^{T/2} dt\sum_{n=0}^{N} C_n{}^2\tfrac{1}{2}\\ &=T\sum_{n=0}^{N} w(f_n)\Delta f\to T\int_0^\infty w(f)df \end{aligned} \tag{3.2}$$

where we have used the limiting process mentioned in connection with Eqs. (2.4).

4, THE STANDARD DEVIATION σ_T OF E

The standard deviation, since its square is the second moment about the average, is given by the rule

$$\sigma_T{}^2=\langle E^2\rangle_{Av}-\bar{E}^2=\langle E^2\rangle_{Av}-m_T{}^2 \tag{4.1}$$

and we have to calculate $\langle E^2\rangle_{Av}$. From (2.5)

$$\begin{aligned} E^2&=\int_{-T/2}^{T/2} dtI_N^2(t)\int_{-T/2}^{T/2} d\tau I_N^2(\tau)\\ &=\int_{-T/2}^{T/2} dt\int_{-T/2}^{T/2} d\tau\sum_{0}^{N} C_nC_mC_pC_q\cos(\omega_n t-\varphi_n)\cos(\omega_m t-\varphi_m)\cos(\omega_p\tau-\varphi_p)\cos(\omega_q\tau-\varphi_q) \end{aligned} \tag{4.2}$$

where the summation extends over $0\leq n, m, p, q\leq N$. The average value of E^2 is

$$\langle E^2\rangle_{Av}=\left(\frac{1}{2\pi}\right)^{N+1}\int_0^{2\pi} d\varphi_0\int_0^{2\pi} d\varphi_1\cdots\int_0^{2\pi} d\varphi_N E^2. \tag{4.3}$$

Let us fix our attention upon the terms which involve φ_1 only. Setting $n=m=p=q=1$ we obtain the integral

$$\frac{1}{2\pi}\int_0^{2\pi} d\varphi_1\cos^2(\omega_1 t-\varphi_1)\cos^2(\omega_1\tau-\varphi_1)=\tfrac{1}{8}[1+2\cos^2\omega_1(t-\tau)].$$

Consequently the contribution to $\langle E^2\rangle_{Av}$ of terms which involve only one phase angle is

$$\tfrac{1}{8}\sum_{n=0}^{N} 4w^2(f_n)(\Delta f)^2\int_{-T/2}^{T/2}dt\int_{-T/2}^{T/2}d\tau[1+2\cos^2\omega_n(t-\tau)]$$

$$\rightarrow\tfrac{1}{2}\Delta f T^2\int_0^\infty w^2(f)df\int_{-T/2}^{T/2}dt\int_{-T/2}^{T/2}d\tau[1+2\cos^2 2\pi f(t-\tau)] \quad (4.4)$$

which approaches zero if T remains fixed.

Now consider those terms which involve φ_1 and φ_2 only. The terms which involve no φ's other than φ_1 and φ_2 are obtained by giving n, m, p, q the values one or two. Thus there are $2^4=16$ such terms. Two of these involve only one phase angle and are of the type discussed just above. Of the remaining 14, 8 contain only the first power of $\cos(\omega_1 t-\varphi_1)$ or of $\cos(\omega_2 t-\varphi_2)$ and hence disappear upon integration. An example of one of these 8 is $n=m=p=1$, $q=2$. The remaining 6 have to be considered one by one. They are obtained by setting

$$\begin{aligned} &n=m=1; \quad p=q=2,\\ &n=m=2; \quad p=q=1,\\ &n=p=1; \quad m=q=2,\\ &n=p=2; \quad m=q=1,\\ &n=q=1; \quad m=p=2,\\ &n=q=2; \quad m=p=1. \end{aligned}$$

The first combination gives

$$\left(\frac{1}{2\pi}\right)^2\int_0^{2\pi}d\varphi_1\int_0^{2\pi}d\varphi_2 C_1^2C_2^2\cos^2(\omega_1 t-\varphi_1)\cos^2(\omega_2\tau-\varphi_2)=C_1^2C_2^2/4. \quad (4.5)$$

The second combination gives the same result. The third combination gives

$$\left(\frac{1}{2\pi}\right)^2\int_0^{2\pi}d\varphi_1\int_0^{2\pi}d\varphi_2 C_1^2C_2^2\cos(\omega_1 t-\varphi_1)\cos(\omega_1\tau-\varphi_1)\cos(\omega_2 t-\varphi_2)\cos(\omega_2\tau-\varphi_2)$$

$$=\frac{C_1^2C_2^2}{4}\cos\omega_1(t-\tau)\cos\omega_2(t-\tau). \quad (4.6)$$

The fourth combination gives the same result. The fifth gives

$$\left(\frac{1}{2\pi}\right)^2\int_0^{2\pi}d\varphi_1\int_0^{2\pi}d\varphi_2 C_1^2C_2^2\cos(\omega_1 t-\varphi_1)\cos(\omega_1\tau-\varphi_1)\cos(\omega_2 t-\varphi_2)\cos(\omega_2\tau-\varphi_2) \quad (4.7)$$

which is the same as the sixth and also as the third and fourth.

Adding these results shows that the contribution to $\langle E^2\rangle_{Av}$ from the terms involving only φ_1 and φ_2 is

$$\int_{-T/2}^{T/2}dt\int_{-T/2}^{T/2}d\tau\frac{C_1^2C_2^2}{2}[1+2\cos\omega_1(t-\tau)\cos\omega_2(t-\tau)]. \quad (4.8)$$

Adding all such terms together gives

$$\langle E^2\rangle_{Av}=\int_{-T/2}^{T/2}dt\int_{-T/2}^{T/2}d\tau\sum_{n=0}^{N-1}\sum_{m=n+1}^{N}\frac{C_n^2C_m^2}{2}[1+2\cos\omega_n(t-\tau)\cos\omega_m(t-\tau)]. \quad (4.9)$$

In writing down this equation we have made use of the fact that the terms involving three or more different φ's contribute nothing to $\langle E^2\rangle_{Av}$ since they disappear upon integration, and that (4.4) vanishes in the limit and consequently may be neglected.

Now

$$\begin{aligned}2\cos\omega_n(t-\tau)\cos\omega_m(t-\tau)&=\cos(\omega_m+\omega_n)(t-\tau)+\cos(\omega_m-\omega_n)(t-\tau)\\&=\cos a(t-\tau)+\cos b(t-\tau)\\&=\cos at\cos a\tau+\sin at\sin a\tau\\&\quad+\cos bt\cos b\tau+\sin bt\sin b\tau\end{aligned}\tag{4.10}$$

where

$$a=\omega_m+\omega_n,\quad b=\omega_m-\omega_n.$$

Hence

$$\int_{-T/2}^{T/2}dt\int_{-T/2}^{T/2}d\tau[1+2\cos\omega_n(t-\tau)\cos\omega_m(t-\tau)]=T^2+\left[\frac{2\sin(aT/2)}{a}\right]^2+\left[\frac{2\sin(bT/2)}{b}\right]^2.\tag{4.11}$$

Equation (4.9) may now be written

$$\langle E^2\rangle_{Av}=\sum_{n=0}^{N-1}\sum_{m=n+1}^{N}\frac{C_n^2C_m^2}{2}\left[T^2+\frac{4\sin^2(\omega_n+\omega_m)\frac{T}{2}}{(\omega_n+\omega_m)^2}+\frac{4\sin^2(\omega_m-\omega_n)\frac{T}{2}}{(\omega_m-\omega_n)^2}\right].\tag{4.12}$$

Because of symmetry we may divide by 2 and write the summation in m from 0 to N with the term $m=n$ omitted. When we pass to the limit we may put in the term corresponding to $m=n$ since it is very small. In fact, according to (4.4), the sum of all $N+1$ terms of this type is of order Δf. The result is

$$\langle E^2\rangle_{Av}=\int_0^\infty w(f_1)df_1\int_0^\infty w(f_2)df_2\left[T^2+\frac{\sin^2\pi(f_1+f_2)T}{\pi^2(f_1+f_2)^2}+\frac{\sin^2\pi(f_1-f_2)T}{\pi^2(f_1-f_2)^2}\right].\tag{4.13}$$

From (4.1)

$$\sigma_T^2=\int_0^\infty w(f_1)df_1\int_0^\infty w(f_2)df_2\left[\frac{\sin^2\pi(f_1+f_2)T}{\pi^2(f_1+f_2)^2}+\frac{\sin^2\pi(f_1-f_2)T}{\pi^2(f_1-f_2)^2}\right].\tag{4.14}$$

We shall investigate this in a later section.

5. THE STANDARD DEVIATION $\sigma_{S,T}$ OF THE ENERGY DIFFERENCE

From (2.6) we have, since the average value of the energy difference is zero

$$\begin{aligned}\sigma_{S,T}^2&=\text{average value}\left[\int_{-(S+T)/2}^{(T-S)/2}dt-\int_{-(T-S)/2}^{(T+S)/2}dtI_N^2(t)\right]^2\\&=\text{average value}\left[\int_{-(S+T)/2}^{(T-S)/2}dt\int_{-(S+T)/2}^{(T-S)/2}d\tau I_N^2(t)I_N^2(\tau)\right.\\&\quad+\int_{-(T-S)/2}^{(T+S)/2}dt\int_{-(T-S)/2}^{(T+S)/2}d\tau I_N^2(t)I_N^2(\tau)-2\int_{-(S+T)/2}^{(T-S)/2}dt\int_{-(T-S)/2}^{(T+S)/2}d\tau I_N^2(t)I_N^2(\tau)\left.\right].\end{aligned}\tag{5.1}$$

The first two terms in (5.1) are equal to each other and to $\sigma_T^2+m_T^2$. Hence

$$\sigma_{S,T}^2=2(\sigma_T^2+m_T^2)-2\text{ average}\int_{-(S+T)/2}^{(T-S)/2}dt\int_{-(T-S)/2}^{(T+S)/2}d\tau I_N^2(t)I_N^2(\tau).\tag{5.2}$$

An expression for the second term may be written down from (4.9) and (4.10). After using the same considerations of symmetry and of the negligibility of the terms for which $m=n$ we obtain

$$2\int_{-(S+T)/2}^{(T-S)/2}dt\int_{-(T-S)/2}^{(T+S)/2}d\tau\sum_{n=0}^{N}\sum_{m=0}^{N}\frac{C_n^2C_m^2}{4}(1+\cos at\cos a\tau+\sin at\sin a\tau+\cos bt\cos b\tau+\sin bt\sin b\tau)\tag{5.3}$$

where $a=\omega_m+\omega_n$, $b=\omega_m-\omega_n$. Typical integrations are

$$\begin{aligned}
\int_{-(S+T)/2}^{(T-S)/2} dt\cos at &= \frac{1}{a}\left(\sin\frac{T-S}{2}a+\sin\frac{S+T}{2}a\right)\\
&= \frac{2}{a}\sin\frac{T}{2}a\cos\frac{S}{2}a,\\
\int_{-(T-S)/2}^{(T+S)/2} d\tau\cos a\tau &= \frac{1}{a}\left(\sin\frac{T+S}{2}a+\sin\frac{T-S}{2}a\right)\\
&= \frac{2}{a}\sin\frac{T}{2}a\cos\frac{S}{2}a,\\
\int_{-(S+T)/2}^{(T-S)/2} dt\sin at &= \frac{-1}{a}\left(\cos\frac{T-S}{2}a-\cos\frac{S+T}{2}a\right)\\
&= \frac{-2}{a}\sin\frac{T}{2}a\sin\frac{S}{2}a,\\
\int_{-(T-S)/2}^{(T+S)/2} d\tau\sin a\tau &= -\frac{1}{a}\left(\cos\frac{S+T}{2}a-\cos\frac{T-S}{2}a\right)\\
&= \frac{2}{a}\sin\frac{T}{2}a\sin\frac{S}{2}a.
\end{aligned} \tag{5.4}$$

Expression (5.3) becomes

$$\sum_{n=0}^{N}\sum_{m=0}^{N}\frac{C_n^2C_m^2}{2}\left[T^2+\left(\frac{2}{a}\sin\frac{T}{2}a\cos\frac{S}{2}a\right)^2-\left(\frac{2}{a}\sin\frac{T}{2}a\sin\frac{S}{2}a\right)^2\right.$$
$$\left.+\left(\frac{2}{b}\sin\frac{T}{2}b\cos\frac{S}{2}b\right)^2-\left(\frac{2}{b}\sin\frac{T}{2}b\sin\frac{S}{2}a\right)^2\right].$$

Putting this in (5.2) and writing, from (4.12)

$$2(\sigma_T^2+m_T^2)=2\langle E^2\rangle_{Av}=\sum_{n=0}^{N}\sum_{m=0}^{N}\frac{C_n^2C_m^2}{2}\left[T^2+\left(\frac{2\sin\frac{T}{2}a}{a}\right)^2+\left(\frac{2\sin\frac{T}{2}b}{b}\right)^2\right]$$

gives

$$\begin{aligned}
\sigma_{S,T}^2 &= \sum_{n=0}^{N}\sum_{m=0}^{N}\frac{C_n^2C_m^2}{2}\left[\left(\frac{2\sin\frac{T}{2}a}{a}\right)^2\left(1-\cos^2\frac{S}{2}a+\sin^2\frac{S}{2}a\right)+\left(\frac{2\sin\frac{T}{2}b}{b}\right)^2\left(1-\cos^2\frac{S}{2}b+\sin^2\frac{S}{2}b\right)\right]\\
&= \sum_{n=0}^{N}\sum_{m=0}^{N}C_n^2C_m^2\left[\left(\frac{2}{a}\sin\frac{T}{2}a\sin\frac{S}{2}a\right)^2+\left(\frac{2}{b}\sin\frac{T}{2}b\sin\frac{T}{2}b\right)^2\right]\\
&= 4\int_0^\infty w(f_1)df_1\int_0^\infty w(f_2)df_2\left[\left(\frac{\sin\pi(f_1+f_2)T\sin\pi(f_1+f_2)S}{\pi(f_1+f_2)}\right)^2+\left(\frac{\sin\pi(f_1-f_2)T\sin\pi(f_1-f_2)S}{\pi(f_1-f_2)}\right)^2\right].
\end{aligned} \tag{5.5}$$

As a partial check on (5.5) we consider the separation S of the intervals to be very large. Then

$$\text{average}\,[E(t_1,T)-E(t_1+S,T)]^2=\text{average}\,(E(t_1,T)-m_T)^2+\text{average}\,(E(t_1+S,T)-m_T)^2=2\sigma_T^2.$$

When S is very large the term $\sin^2\pi(f_1\pm f_2)S$ is, in effect, the same as its average value of $\frac{1}{2}$. Hence

$$\sigma_{S,T}^2=\frac{4}{2}\sigma_T^2,$$

upon using the integral (4.14) for σ_T^2.

6. EVALUATION OF m_T, σ_T FOR AN IDEAL FILTER

Let the pass band be $f_a \leq f \leq f_b$. Then we take

$$w(f) = w_0 \text{ watts per cycle per second}$$

in this band and $w(f) = 0$ outside the band.

From (3.2)

$$m_T = T\int_{f_a}^{f_b} w(f)df = w_0 T(f_b - f_a). \tag{6.1}$$

From (4.14)

$$\sigma_T{}^2 = w_0{}^2 \int_{f_a}^{f_b} df_1 \int_{f_a}^{f_b} df_2 \left[\frac{\sin^2 \pi(f_1+f_2)T}{\pi^2(f_1+f_2)^2} + \frac{\sin^2 \pi(f_1-f_2)T}{\pi^2(f_1-f_2)^2}\right]. \tag{6.2}$$

In order to evaluate this integral we first consider the expansion

$$\frac{\sin^2 x}{x^2} = \frac{1}{2x^2}(1-\cos 2x) = \frac{1}{2x^2}\sum_{n=1}^{\infty} \frac{(2x)^{2n}(-)^{n-1}}{(2n)!} = \sum_{n=1}^{\infty} \frac{2^{2n-1}x^{2n-2}(-)^{n-1}}{(2n)!}. \tag{6.3}$$

Using this expansion in (6.2)

$$\sigma_T{}^2 = w_0{}^2 T^2 \sum_{n=1}^{\infty} \frac{2^{2n-1}(-)^{n-1}}{(2n)!} \int_{f_a}^{f_b} df_1 \int_{f_a}^{f_b} df_2 [(\pi[f_1+f_2]T)^{2n-2} + (\pi[f_1-f_2]T)^{2n-2}].$$

Now

$$\int_{f_a}^{f_b} df_1 \int_{f_a}^{f_b} df_2 (f_1+f_2)^{2n-2} = \int_{f_a}^{f_b} df_1 \frac{1}{(2n-1)}[(f_1+f_b)^{2n-1} - (f_1+f_a)^{2n-1}]$$

$$= \frac{1}{(2n-1)2n}[(2f_b)^{2n} - (f_a+f_b)^{2n} - (f_b+f_a)^{2n} + (2f_a)^{2n}] \tag{6.4}$$

$$\int_{f_a}^{f_b} df_1 \int_{f_a}^{f_b} df_2 (f_1-f_2)^{2n-2} = \int_{f_a}^{f_b} df_1 \frac{1}{(2n-1)}[-(f_1-f_b)^{2n-1} + (f_1-f_a)^{2n-1}]$$

$$= \frac{1}{(2n-1)2n}[-0 + (f_a-f_b)^{2n} + (f_b-f_a)^{2n} - 0] = \frac{2(f_b-f_a)^{2n}}{2n(2n-1)}. \tag{6.5}$$

Whence

$$\sigma_T{}^2 = 2w_0{}^2 T^2 \sum_{n=1}^{\infty} \frac{(-)^{n-1}(2\pi T)^{2n-2}}{(2n)!(2n-1)(2n)}[(2f_b)^{2n} - 2(f_a+f_b)^{2n} + (2f_a)^{2n} + 2(f_b-f_a)^{2n}]. \tag{6.6}$$

The function

$$F(x) = \sum_{n=1}^{\infty} \frac{(-)^{n-1}x^{2n-2}}{(2n)!(2n-1)(2n)} \tag{6.7}$$

plays an important part in the theory of the energy distribution in the output current of an ideal band pass filter. For small values of x it may be computed from the series. For large values of x we have

$$F(x) \sim \frac{\pi}{2x} - \frac{(\log_e x + 1 + .5772)}{x^2}. \tag{6.8}$$

This is obtained from the exact expression

$$x^2 F(x) = Ci(x) + xSi(x) + \cos x - \log_e x - 1.5772$$

and the asymptotic expansions

$$Ci(x) \sim \sin x/x,$$

$$Si(x) \sim \pi/2 - \cos x/x.$$

TABLE I.

x	$F(x)$	x	$F(x)$
0	0.25	20	0.0671
1	.24657	30	.0468
3	.2222	50	.0292
5	.18628	100	.0151
7	.15289	200	.00768
10	.118	400	.00388
16	.081	1000	.00156

TABLE II.

$2\pi T(f_b-f_a)$	σ_T/m_T
2	0.973
5	.863
10	.688
20	.518
50	.342
100	.246
400	.124
1000	.079

The exact expression is obtained by multiplying the series (6.7) by x^2, differentiating twice, and then integrating the resulting differential equation, namely

$$x^2\frac{d^2}{dx^2}x^2F(x)=1-\cos x.$$

Representative values of $F(x)$ are given in Table I. The values for $x>7$ are computed from the asymptotic expression. At this point the error is about one part in a 1000.

From (6.6)

$$\sigma_T^2=2w_0^2T^2[4f_b^2F(4\pi Tf_b)+4f_a^2F(4\pi Tf_a) -2(f_a+f_b)^2F(2\pi T(f_a+f_b))+2(f_b-f_a)^2F(2\pi T(f_b-f_a))]. \quad (6.9)$$

For very small values of T this equation and Eq. (6.1) for m_T show that

$$\sigma_T\approx\sqrt{2}w_0T(f_b-f_a)=\sqrt{2}m_T$$

and for very large values of T, irrespective of the relative values of f_b and f_a,

$$\sigma_T^2\approx w_0^2T(f_b-f_a), \quad \sigma_T/m_T\approx 1/[T(f_b-f_a)]^{\frac{1}{2}}.$$

By using the asymptotic expansion for $F(x)$ it may be shown that when the mid-band frequency is very large in comparison with the band width we have,

$$\sigma_T^2\approx[2w_0T(f_b-f_a)]^2F[2\pi T(f_b-f_a)], \quad (6.10)$$

provided $T>0$. This result may also be obtained by letting $f_b+f_a\to\infty$ in the integral (4.14) for σ_T^2.

The ratio σ_T/m_T is given by

$$\sigma_T/m_T=2\{F[2\pi T(f_b-f_a)]\}^{\frac{1}{2}} \quad (6.11)$$

which has been computed and plotted (see Table II). When $T\to\infty$ we have, in accordance with the general result stated above,

$$\sigma_T^2\to w_0^2T(f_b-f_a)=w_0m_T.$$

An examination of the curve suggests that σ_T/m_T is unity at $T=0$. The true value is $\sqrt{2}$, but it drops to the value unity very quickly as T increases, the rapidity of the drop depending upon the mid-band frequency.

7. EVALUATION OF $\sigma_{S,T}^2$ FOR IDEAL FILTER

We use expression (5.5) for $\sigma_{S,T}^2$ modified for an ideal filter:

$$\sigma_{S,T}^2=4w_0^2\int_{f_a}^{f_b}df_1\int_{f_a}^{f_b}df_2\left[\left(\frac{\sin\pi(f_1+f_2)T\sin\pi(f_1+f_2)S}{\pi(f_1+f_2)}\right)^2+\left(\frac{\sin\pi(f_1-f_2)T\sin\pi(f_1-f_2)S}{\pi(f_1-f_2)}\right)^2\right]. \quad (7.1)$$

If we let $f_a+f_b\to\infty$ with f_b-f_a remaining finite, the part of the integrand involving f_1+f_2 contributes terms of the order of

$$(f_b-f_a)^2/f_a^2\to 0.$$

We assume that $(f_b-f_a)/f_a\to 0$ and obtain

$$\sigma^2_{S,T}=4w_0^2\int_{f_a}^{f_b}df_1\int_{f_a}^{f_b}df_2\left(\frac{\sin\pi(f_1-f_2)T\sin\pi(f_1-f_2)S}{\pi(f_1-f_2)}\right)^2. \tag{7.2}$$

As a first step in evaluating this integral we derive the series

$$\begin{aligned}\frac{4\sin^2\alpha x\sin^2\alpha y}{\alpha^2}&=\frac{1}{\alpha^2}(1-\cos 2\alpha x)(1-\cos 2\alpha y)\\&=\frac{1}{\alpha^2}[1-\cos 2\alpha x-\cos 2\alpha y+\tfrac{1}{2}\cos 2\alpha(x+y)+\tfrac{1}{2}\cos\alpha(x-y)]\\&=\sum_{n=2}^{\infty}\frac{(-)^n 2^{2n}\alpha^{2n-2}}{(2n)!}[-x^{2n}-y^{2n}+\tfrac{1}{2}(x+y)^{2n}+\tfrac{1}{2}(x-y)^{2n}].\end{aligned}$$

When we put

$$\alpha=\pi(f_1-f_2),\quad x=T,\quad y=S$$

in this formula and use it in (7.2) there results

$$\sigma^2_{S,T}=w_0^2\sum_{n=2}^{\infty}\frac{(-)^n 2^{2n}\pi^{2n-2}}{(2n)!}(-T^{2n}-S^{2n}+\tfrac{1}{2}(S+T)^{2n}+\tfrac{1}{2}(S-T)^{2n})\int_{f_a}^{f_b}df_1\int_{f_a}^{f_b}df_2(f_1-f_2)^{2n-2}.$$

Using (6.5) gives

$$\begin{aligned}\sigma^2_{S,T}&=w_0^2\sum_{n=2}^{\infty}\frac{(-)^n 2^{2n}\pi^{2n-2}}{(2n)!}\frac{2(f_b-f_a)^{2n}}{2n(2n-1)}(-T^{2n}-S^{2n}+\tfrac{1}{2}(S+T)^{2n}+\tfrac{1}{2}(S-T)^{2n})\\&=8w_0^2(f_b-f_a)^2\sum_{n=1}^{\infty}\frac{(-)^{n-1}[2\pi(f_b-f_a)]^{2n-2}}{(2n)!(2n)(2n-1)}(T^{2n}+S^{2n}-\tfrac{1}{2}(S+T)^{2n}-\tfrac{1}{2}(S-T)^{2n})\end{aligned} \tag{7.3}$$

which may be expressed in terms of $F(x)$ defined by (6.7).

When we set $S=T$ we get

$$\sigma^2_{T,T}=8w_0^2(f_b-f_a)^2T^2[2F[2\pi(f_b-f_a)T]-\tfrac{1}{2}\cdot 2^2F[2\pi\cdot 2T(f_b-f_a)]],$$

$$\sigma^2_{T,T}=[4w_0T(f_b-f_a)]^2[F[2\pi(f_b-f_a)T]-F[4\pi(f_b-f_a)T]].$$

As $T\to\infty$

$$\sigma^2_{T,T}\to 4w_0^2T(f_b-f_a)\cdot\frac{\pi}{2}\left[\frac{4T(f_b-f_a)T}{2\pi(f_b-f_a)T}\right][1-\tfrac{1}{2}]=2w_0^2T(f_b-f_a)$$

which is twice the value of σ_T^2 given by the limit of (6.10), and this is as it should be. Taking the square root of the above expression for $\sigma^2_{T,T}$ and dividing by $m_T=w_0T(f_b-f_a)$ gives

$$\sigma_{T,T}/m_T=4[F(u)-F(2u)]^{\frac{1}{2}} \tag{7.4}$$

where

$$u=2\pi T(f_b-f_a).$$

8. BAND PASS FILTER WITH NORMAL-LAW CHARACTERISTIC

Suppose that instead of an ideal band pass filter we have one with a normal law characteristic.

$$A(f)=\exp\left[-\frac{(f-f_0)^2}{2\sigma^2}\right],$$

$$w(f)=w_0A^2(f)=w_0\exp\left[-\frac{(f-f_0)^2}{\sigma^2}\right], \tag{8.1}$$

$$m_T=T\int_0^\infty w(f)df=w_0T\sigma\sqrt{\pi}. \tag{8.2}$$

In evaluating the last integral we have assumed $f_0\gg\sigma$. An ideal band pass filter which would pass the same average amount of energy would have a band width of

$$f_b-f_a=\sigma\sqrt{\pi}. \tag{8.3}$$

To get σ_T we use (4.14) with the f_1+f_2 terms omitted because $f_0\gg\sigma$. For the same reason we may replace the lower limits of integration by $-\infty$'s without changing the value of the integral appreciably. Setting

$$x=(f_1-f_0)/\sigma,\quad y=(f_2-f_0)/\sigma$$

gives

$$\begin{aligned}\sigma_T^2&=w_0^2\int_{-\infty}^{+\infty}dx\int_{-\infty}^{+\infty}dye^{-x^2-y^2}\frac{\sin^2\pi(x-y)\sigma T}{\pi^2(x-y)^2}\\&=\frac{w_0^2}{2\pi^2}\int_{-\infty}^{+\infty}due^{-u^2}\frac{\sin^2(\pi\sqrt{2}\sigma T)u}{u^2}\int_{-\infty}^{+\infty}dve^{-v^2}\\&=w_0^2\frac{\sqrt{\pi}}{2\pi^2}\int_{-\infty}^{+\infty}due^{-u^2}\frac{\sin^2 au}{u^2}.\end{aligned}$$

In going from the first double integral to the second we have set

$$x-y=\sqrt{2}u,\quad x+y=\sqrt{2}v,\quad x^2+y^2=u^2+v^2,\quad dxdy=dudv.$$

In the last integral

$$a=\sqrt{2}\pi\sigma T=(2\pi)^{\frac{1}{2}}T\sigma\sqrt{\pi}=(2\pi)^{\frac{1}{2}}m_T/w_0=(2\pi)^{\frac{1}{2}}T(f_b-f_a).$$

By expanding

$$\sin^2 au/u^2$$

in a power series and integrating termwise we obtain

$$\sigma_T^2=w_0^2\frac{a^2}{2\pi}\sum_{n=0}^{\infty}\frac{(-)^na^{2n}}{(n+1)!(2n+1)}.$$

If

$$u=2\pi T(f_b-f_a)=(2\pi)^{\frac{1}{2}}a$$

then

$$m_T=w_0\frac{a}{(2\pi)^{\frac{1}{2}}}=w_0\frac{u}{2\pi},$$

$$\sigma_T^2=w_0^2\frac{u^2}{4\pi^2}\sum_{n=0}^{\infty}\frac{(-)^nu^{2n}}{(2\pi)^n(n+1)!(2n+1)},$$

$$y_B=\frac{\sigma_T}{m_T}=\left[\sum_{n=0}^{\infty}\frac{(-)^nu^{2n}}{(2\pi)^n(n+1)!(2n+1)}\right]^{\frac{1}{2}}.$$

As $x\to\infty$

$$y_B\to[(2\pi)^{\frac{1}{2}}/x-2\pi/x^2]^{\frac{1}{2}}.$$

9. FLUCTUATION OF CHARGE AS A FUNCTION OF INTERVAL LENGTH

Here we consider a problem which apparently is of less technical interest than the one treated above, but which is much simpler. In view of this, we shall merely state the problem and give the answers, leaving the proofs to the reader.

In place of the energy E consider the charge Q which flows past a point in the circuit during the interval (t_1, t_1+T).

$$Q \equiv Q(t_1, T) = \int_{t_1}^{t_1+T} I(t)dt. \tag{9.1}$$

If we are interested in the average current, it may be obtained by dividing Q by T. If the starting point t_1 of the interval is chosen at random, Q is a random variable. Its average value is zero and the square of its standard deviation is

$$\langle Q^2(t_1, T)\rangle_{Av} = \frac{1}{\pi^2}\int_0^\infty w(f)\sin^2 \pi fT \frac{df}{f^2} \tag{9.2}$$

where $w(f)$ is the energy spectrum of the noise current $I(t)$ just as before.

The standard deviation of the difference between two Q's each of length T whose starting points are separated by a time S is given by the square root of

$$\text{Average value of } [Q(t_1, T)-Q(t_1+S, T)]^2 = \frac{4}{\pi^2}\int_0^\infty w(f)\sin^2 \pi fT \sin^2 \pi fS \frac{df}{f^2}. \tag{9.3}$$

As $S\to\infty$ the value of (9.3) approaches twice that of $\langle Q^2\rangle_{Av}$ as given by (9.2), as is to be expected.

The average value of the product of two Q's of lengths T and T' whose starting points are separated by a time S is as follows:

$$\text{Average value of } Q(t_1, T)Q(t_1+S, T') = \frac{1}{\pi^2}\int_0^\infty w(f)\sin \pi fT \sin \pi fT' \cos \pi f(T'-T+2S)\frac{df}{f^2}. \tag{9.4}$$

When $w(f)$ is of the form appropriate to ideal band pass filters all of the integrals of this section may be expressed in terms of trigonometrical, integral sine, and integral cosine functions.

APPENDIX

It appears difficult to give a rigorous justification for the representation assumed in Eq. (2.3). However, a line of thought which perhaps makes it plausible runs as follows.

Consider the source of noise to be the shot effect in a vacuum tube or some similar mechanism for which the current $I(t)$ at time t may be expressed as the sum of the effects of a great number of independent events:

$$I(t) = \sum_{k=-\infty}^{+\infty} F(t-t_k). \tag{1A}$$

$F(t)$ is the current produced by a single event occurring at $t=0$, and the kth event occurs at t_k.

Suppose we have an oscillogram of $I(t)$ extending over a very long period of time. We may cut it up into a great many intervals of length T'. A Fourier analysis of each interval yields a set of Fourier coefficients, the analysis for a typical interval being

$$I(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty}\left(a_n \cos\frac{2\pi nt}{T'} + b_n \sin\frac{2\pi nt}{T'}\right). \tag{2A}$$

When T' is much greater than the interval over which $F(t)$ is appreciably different from zero, the values of the a_n's and b_n's for a particular interval depend upon the number and spacing of the events occurring at the t_k's within that interval. Thus, the a's and b's for one interval may be quite different from those in a second interval. In fact, there is reason to believe that, for the purpose we have in mind, we may regard the a's and b's as independent random variables which are distributed normally about zero.

The steps in the reasoning leading to this result are rather involved. Here we state only the fundamental theorem and warn the reader that there are some points in its derivation where further work is necessary for complete rigor: Let the $2N$ quantities $a_1, \cdots a_N, b_1, \cdots b_N$ define a point in $2N$ dimensional space. There will be one point corresponding to each

interval, and the ensemble of intervals will define an ensemble of points. The probability density of this ensemble is

$$(1+\eta)(2\pi)^{-N}\sigma_1^{-2}\cdots\sigma_N^{-2}\exp\left[-\sum_{n=1}^{N}\frac{x_n^2+y_n^2}{2}\right]$$

where, $x_n=a_n/\sigma_n$, $y_n=b_n/\sigma_n$, $\sigma_n^2=\nu T'(C_n^2+S_n^2)/2$

$$C_n+iS_n=\frac{2}{T'}\int_{-\infty}^{+\infty}F(t)\exp\frac{i2\pi nt}{T'}dt.$$

ν is the average number of events per second, and η is a correction term. When all the x_n's and y_n's are equal to x, η is of the order of

$$x^3N^2(\nu T')^{-\frac{1}{2}}.$$

Since ν is ordinarily an extremely large number, η is negligibly small and the resulting form of the probability density function shows that the a's and b's are independent and are distributed normally about zero.

Now suppose the Fourier series expression (2A) for $I(t)$ to be placed in the definition (1.1) for $E(t_1, T)$, it being assumed that $T<T'$. Let t_1 take on a succession of values $t_0, t_0+T', t_0+2T', \cdots$ such that t_0, t_0+T lies within the first of the intervals of length T'; $t_0+T', t_0+T'+T$ within the second interval; and so on. Then the first $E(t_1, T)$ will be a function of the a's and b's corresponding to the first interval; the second $E(t_1, T)$ will be a function of the a's and b's corresponding to the second interval; and so on. This ensemble of values of $E(t_1, T)$ will have a distribution which may be determined, in theory, from the distribution of the a's and b's which, as mentioned above, may be regarded as normal.

Thus, when the noise current is of the form (1A), we may obtain its statistical properties by representing it as a Fourier series whose coefficients are distributed normally about zero and are independent. The reader may ask, "Why not use such a representation instead of (2.3)?" The answer is that for the purposes of this paper (2.3) is more convenient and leads to the same results. This may be verified by actually carrying out the work for both representations. Perhaps a formal proof could be established along the following lines. Consider a small group of terms of (2.3) over a short interval of time starting at $t=0$. Let the group be so small and the time so short that C_n, cos w_nt, and sin w_nt do not change appreciably over it. Then the group may be written as

$$\sum_{n=n_1}^{n_2}C_n\cos(\omega_nt-\varphi_n)\approx C_{n1}\cos\omega_{n1}t(\cos\varphi_{n1}+\cdots+\cos\varphi_{n2})+C_{n1}\sin\omega_{n1}t(\sin\varphi_{n1}+\cdots+\sin\varphi_{n2}).$$

The frequency range covered by the group is $(n_2-n_1)\Delta f$. This may be held fixed and at the same time the number n_2-n_1 of terms in the group increased by decreasing Δf. Since the coefficients of cos $w_{n1}t$ and sin $w_{n1}t$ are the sums of independent random variables, it follows from the central limit theorem in probability that they approach two independent and normally distributed random variables.

An Experimental Study of the Tone Quality of the Boehm Clarinet

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Several theories of clarinet action have been developed, but have been based on rather fragmentary experimental data. The present paper offers such a description of the instrument as is essential to this particular study, and a consideration of the tone quality at the bell of the instrument in the three conventional registers. Special consideration is given to the harmonic structure of the tones and its variation throughout the pitch range. All pianissimo tones are extremely simple, consisting almost entirely of the fundamental. For this reason, the investigation of only the forte tones is necessary for the study of harmonic structure, since the mezzoforte tones represent a transitional stage. The harmonic structure simplifies in progressing from the lowest to the highest pitch with the extremes representing remarkable contrast. In the whole range of forty tones there are only five, blown forte, in which the percent of total energy in the fundamental exceeds fifty percent. The tone B_4, which has the maximum energy, 88.2 percent, in the fundamental and no harmonics of comparable intensity, is the orchestral tuning note. The characteristic tone quality of the clarinet, often described as reedy or hollow, and most evident in the low register, appears to be due to the relatively strong odd numbered partial tones and to be determined mostly by the first eight partials.

INTRODUCTION

THE clarinet is unique among the instruments of the woodwinds, since the twelfth instead of the octave is produced on overblowing. In this respect, its action resembles that of a closed pipe, and it was once thought that only the odd harmonics were present or at most there were only traces of even harmonics.[1] Miller[2] has shown in several analyses that, in the case of one tone, "the seventh partial contains 8 percent of the total loudness, while the eighth, ninth, and tenth contain 18, 15, and 18 percent, respectively."

We have extended the observations and analyses over all the tones in the range of the instrument, which is slightly over three octaves. Notating[3] "middle *C*" as C_4, as in Fig. 1, the useful range of the clarinet in $B\flat$ extends from E_3 to G_6 as read by the performer, the actual sounds being two semi-tones below the notation. In this article the notes are indicated first as read by the performer and then, in parentheses, as actually sounded. All results are for the $B\flat$ clarinet.

THE THREE DIVISIONS IN RANGE

Clarinetists regard notes $A\flat_4$ ($G\flat_4$), A_4 (G_4), and $B\flat_4$ ($A\flat_4$) as transition tones between the low and middle registers but acoustically they do not require special consideration as they are produced by a gradual shortening of the effective tube length. The tone quality of the clarinet is quite different in the various parts of its compass. Also, the method of fingering suggests that, for the purposes of study, its entire pitch range be divided into the three conventional registers as indicated in Fig. 1.

CLARINET TUBE

The tube of the $B\flat$ clarinet measures about 67.0 cm over-all. Its cross section is smallest at the tip of the mouthpiece between the reed and the palate, expanding into a cylindrical tube within a length of about 3.1 cm. This cylinder continues until about 15 cm from the open end where the cross section begins to enlarge into the final flare or bell with a maximum diameter of about 6 cm. The diameter of the cylindrical bore varies from 1.47 to 1.50 cm in the different

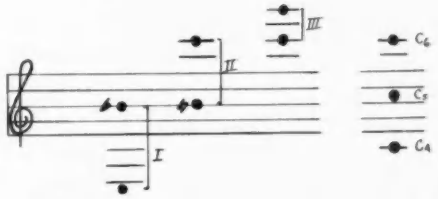


FIG. 1. (I) Low or chalumeau register. Gradual tube shortening. (II) Middle or clarion register. Same fingering as I. Register hole open. (III) High register. More complicated fingerings. Register hole open. Octave notation. (The lower note should be $C\sharp_6$.)

[1] H. Helmholtz, *Sensations of Tone* (Longmans, Green, London), translation by Ellis, p. 99.
[2] D. C. Miller, *The Science of Musical Sounds* (Macmillan, 1926), p. 201.
[3] R. W. Young, J. Acous. Soc. Am. **11**, 134–139 (1939).

high grade instruments. Small variations in the bore, and of doubtful utility, are sometimes introduced by some manufacturers.

No detailed measurements of positions, sizes, or depths of tone holes, pad lifts, and the like are presented since they vary somewhat with different manufacturers and are scarcely germane to the purposes of this paper.

REED AND THEORY OF ACTION

Since the playing quality of the fitted reed is determined not by its linear dimensions alone but also by the elasticity of the cane, the player must alter the dimensions of the reed to suit the design of the mouthpiece as well as the elasticity of the cane.

The length of the reed is about 6.5 cm and the width across its thin tip about 1.4 cm. Often the width is tapered to about 1.2 cm at the butt or thick end. The "lay" of the mouthpiece curves away from the flat side of the reed as the thin tip is approached, thus forming the aperture which is alternately closed and opened when a properly fitted reed vibrates under control of the player's embouchure. Air pressure in the mouth bends the reed inward, which tends to close the opening of the mouthpiece. The flat side of the reed makes contact with the mouthpiece, while the other side is characteristically tapered to a thin edge. The optimum adjustment of this latter curve with a given quality of cane and a given mouthpiece is a delicate and difficult operation.

As the reed bends inward, its effective vibrating length is shortened by the contact of both side edges with the mouthpiece (Fig. 2).

The following explanation illustrates how odd harmonics are generated, but the even harmonics have been accounted for[4] only by more involved consideration. As the reed begins to close the aperture, a condensation has started down the tube. By the time the condensation has reached the bell or the first open hole, the reed has closed the aperture. The condensation is now reflected from the open end as a rarefaction. But this rarefaction, due to its nature, cannot open the reed upon reaching the mouthpiece, and hence is reflected as a rarefaction for a second trip down the tube. Meanwhile the reed is still in its closed position. When the rarefaction reaches the open end, it will now be reflected as a condensation. As this condensation approaches the mouthpiece, it will gradually cause the reed to open. Thus we see that the reed has made one complete cycle while the initial sound disturbance has traveled four lengths of the tube. This process will now repeat itself. It is important to note that the reed is in its closed position for at least half of the entire period.[5] The aperture, after once being closed, can be opened only when a reflective pulse of condensation increases the air pressure under the reed to a value which is sufficient, with the aid of the reed's elastic forces, to move it outward against the air pressure in the mouth. Thus the large acoustic impedance at the mouthpiece

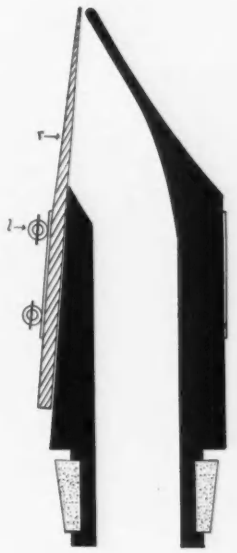


FIG. 2. Clarinet mouthpiece. *r*—reed: *l*—ligature.

FIG. 3. The Boehm system clarinet, 17 keys, 6 rings.

[4] R. N. Ghosh, J. Acous. Soc. Am. **9**, 255–264 (1938); P. Das, Ind. J. Phys. **6**, 230 (1931).

[5] C. S. McGinnis and C. Gallagher, J. Acous. Soc. Am. **12**, 529–531 (1941).

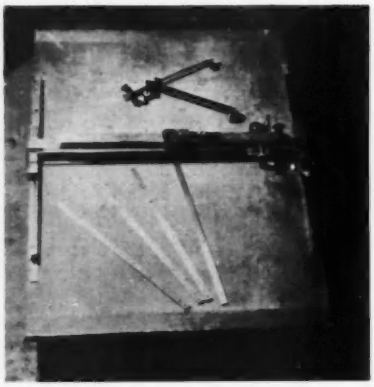


FIG. 4. The harmonic analyzer.

has apparently caused the action to resemble that of a closed pipe, for the sound has traveled four times the tube length for one cycle of the generator (Fig. 3).

METHOD OF FINGERING

The standard 17 key, 6 ring clarinet has 25 tone holes including the open bell. Of the 24 lateral holes, half are normally open and half normally closed, but all may be closed either directly with the fingers or by appropriate mechanism, thus producing the lowest tone E_3 (D_3). All succeeding higher tones in the low register are produced by opening holes progressively nearer the mouthpiece, the top-most hole being used for $B\flat_4$ ($A\flat_4$). This is known as the "register" or "speaker" hole. It is kept open during the production of all higher sounds.

The middle register is produced by exactly the same fingering as the low register except that the register hole is kept open. Its effect is to obliterate the sounds of the fundamentals of the low register and instead to allow the twelfths above, e.g., B_4 (A_4) to C_6 ($B\flat_5$) of the middle register, to act as fundamentals.

The high register is produced by more complicated fingering.[6]

APPARATUS

The clarinet tones were received by either of two piezoelectric pressure microphones. One, of power level −48 db, zero level being taken at 1 volt per bar, was an Astatic D-104. The other was a Brush R22, a sound cell type of power level −70 db and the same zero level. Although the frequency-response characteristics were essentially flat, it was sometimes necessary to make corrections for high frequency partials.

The signal from the microphone was impressed upon a cathode-ray oscillograph. Before the signal was impressed, however, the base line alone was photographed, and then, with the signal e.m.f. applied, the curve was added. With the short-persistence blue screen and Super Ortho Press film, the exposures were 0.01 second at aperture $f:4.5$. The film size was $3\frac{1}{4}\times4\frac{1}{4}$ inches. The curve was enlarged to a base line 12 inches long and the enlargement analyzed with a mechanical harmonic analyzer (Fig. 4).[7]

Each curve can be represented by a Fourier series,

$$y=f(x)=A_1\sin x+A_2\sin 2x+\cdots+A_n\sin nx+B_0+B_1\cos x+B_2\cos 2x+\cdots+B_n\cos nx.$$

The analyzer, which can be used up to the 30th harmonic, gives readings from which the coefficients above are derived. The amplitude of the nth harmonic is given by $(A^2{}_n+B^2{}_n)^{\frac{1}{2}}$. Since the intensity of each harmonic is proportional to

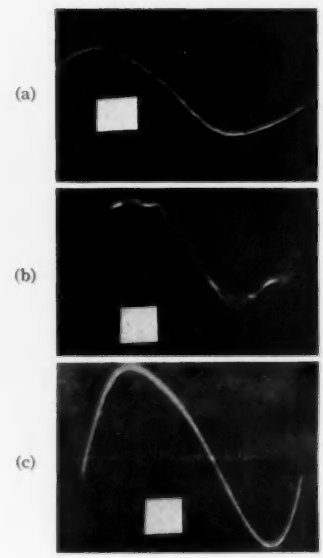
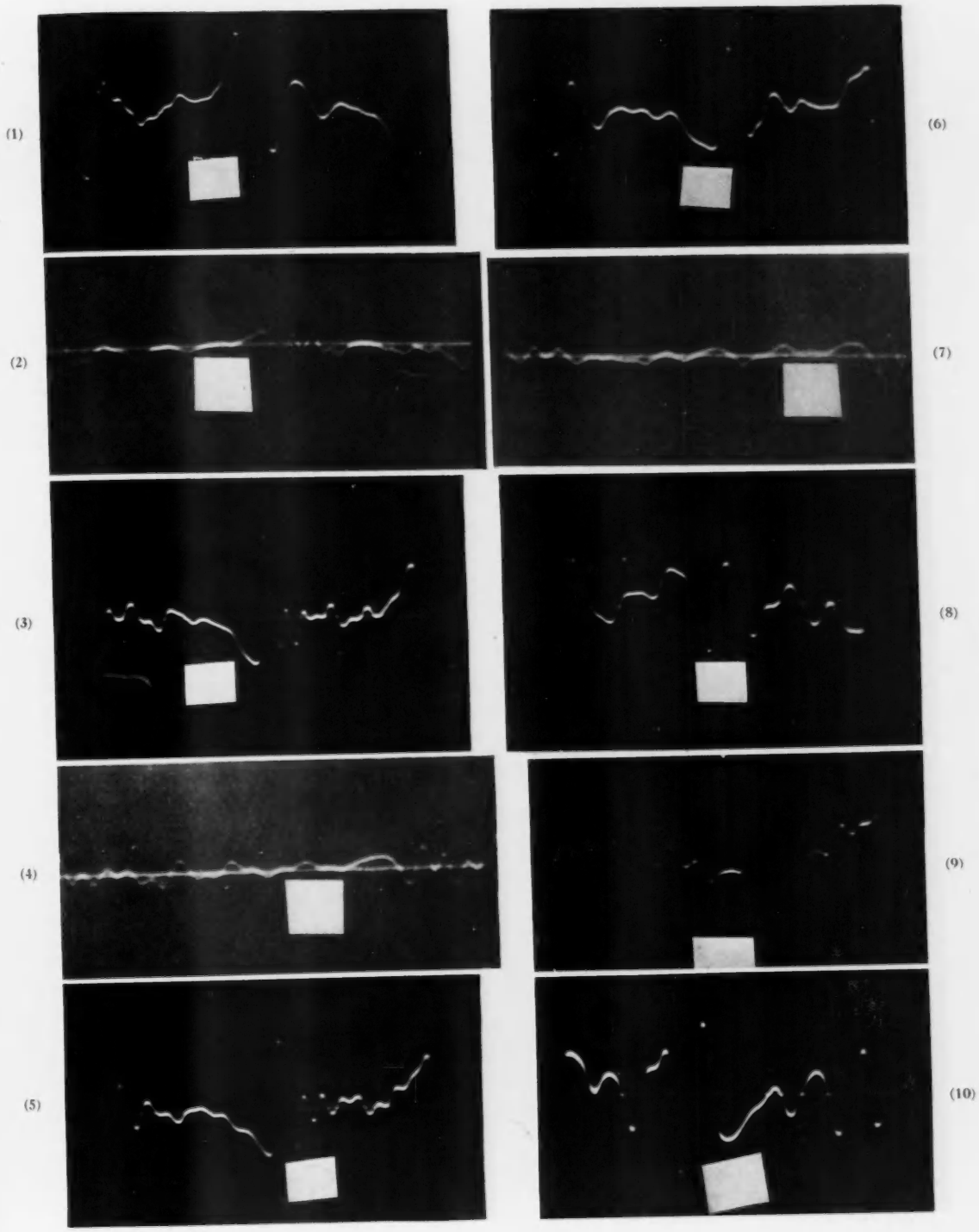


FIG. 5. Pianissimo tones. (a)—$E_3(D_3)$; (b)—$E_5(D_5)$; (c)—$E_6(D_6)$.

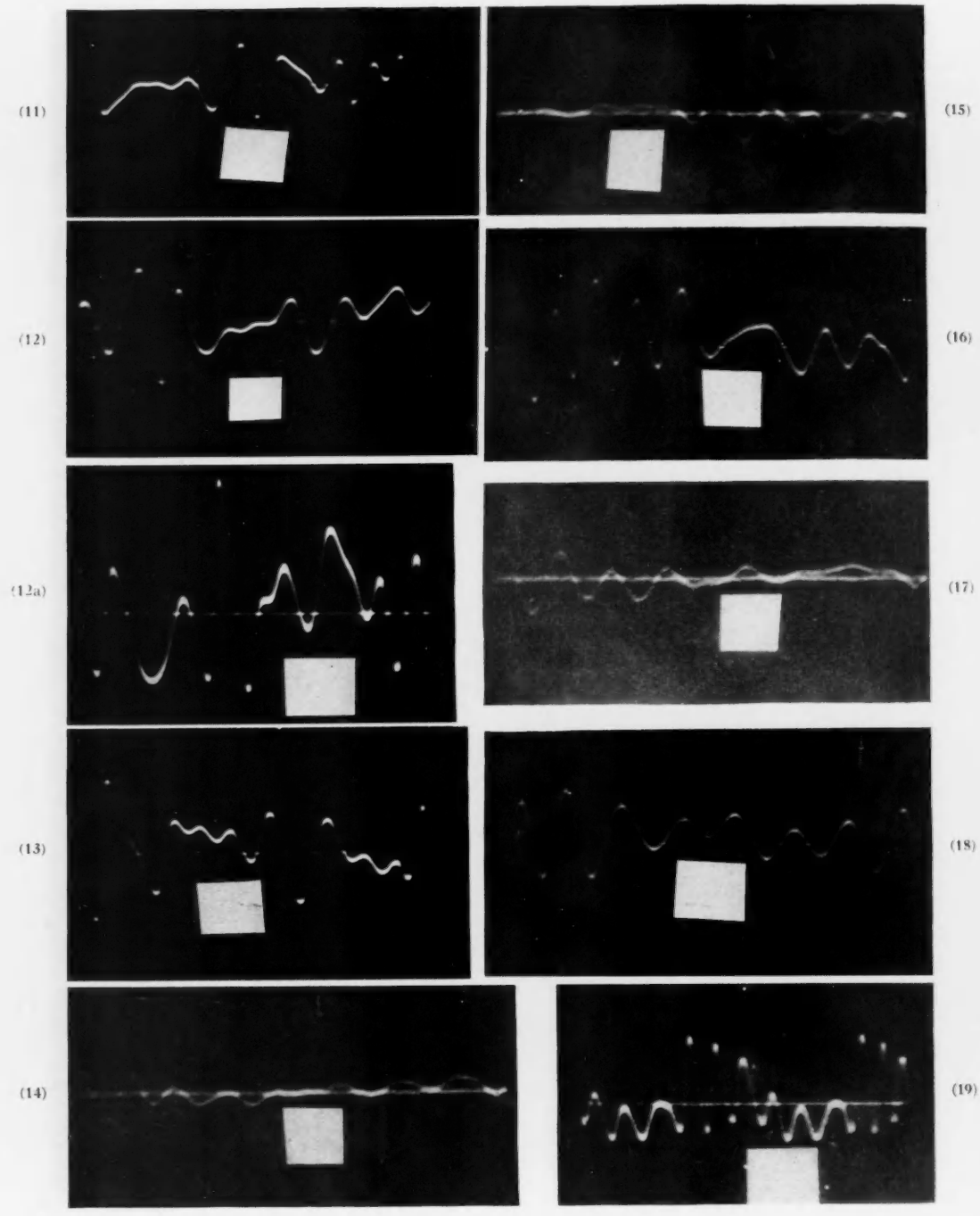
[6] H. Klosé, *Method for the Clarinet* (Carl Fischer), p. 5.

[7] W. Koenig, Jr., Bell Lab. Record **13**, 258–263 (1935); E. A. Tamkin, *A Harmonic Analyzer*, Thesis (Temple University Library, June, 1936).



(a)

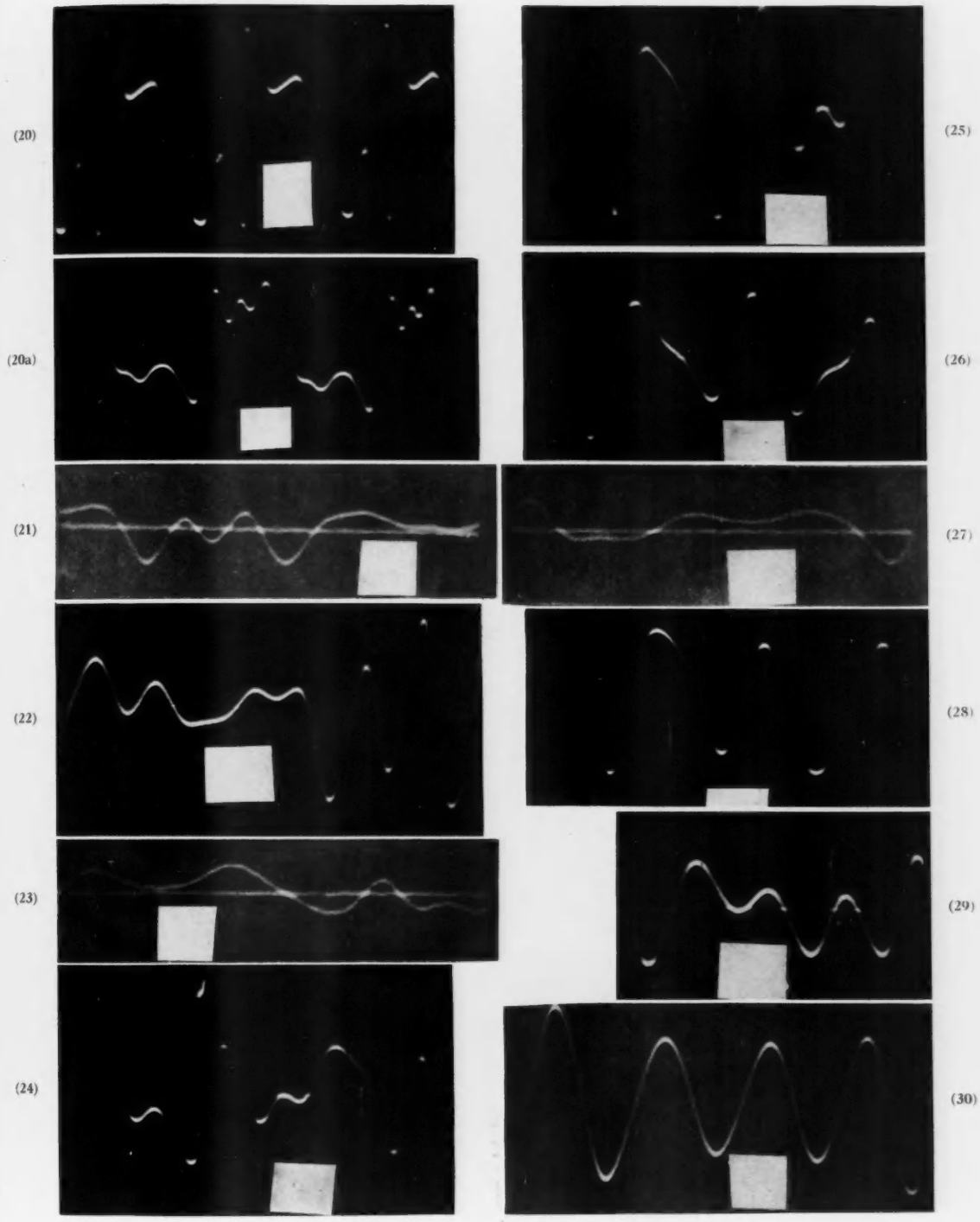
FIG. 6. Sound curves.



(b)

FIG. 6. (Continued.)

the square of the maximum value p_0 of the excess pressure variation, the relative physical intensities of the harmonics are easily calculated. These intensities are referred to in the conclusions. Obviously, amplitude comparisons would have little significance so far as intensity or loudness is concerned. All photographs were taken in a cubical sound room about 2.5 meters on a side and with walls, floor, and ceiling lined with 10 cm of rock wool supported by batting.



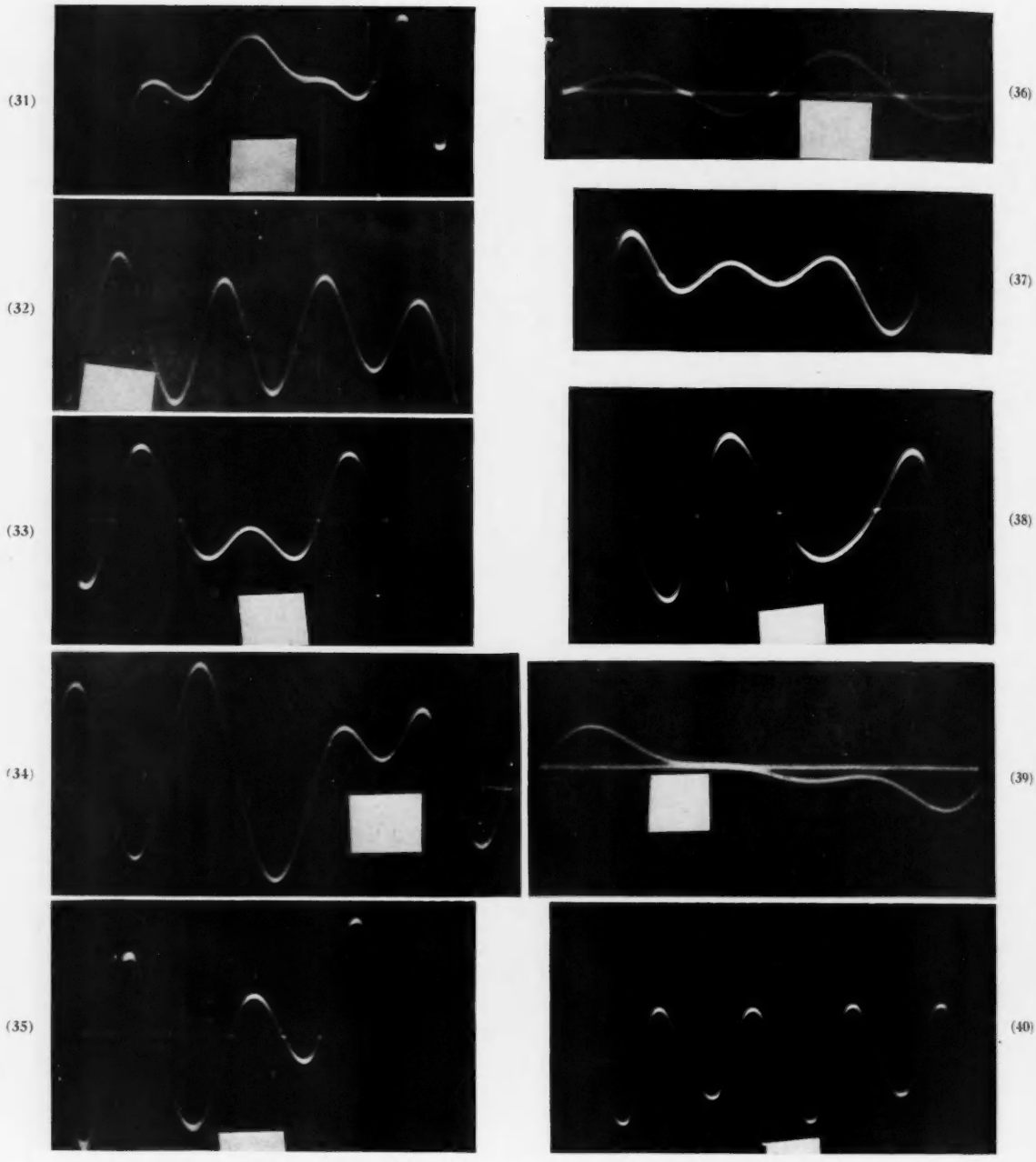
(c)

FIG. 6. (Continued.)

The microphone was placed about three inches from the bell of the clarinet and on a line with its axis. The wave shape on the screen was independent of the position of the microphone and the clarinet in the room.

RESULTS

The first experiments were directed to show the accepted theory that the greater the intensity, the stronger and more numerous are the harmonics. Three levels of intensity, as com-



(d)

FIG. 6. (Continued.)

monly interpreted by musicians, were studied: piano, *p*; mezzoforte, *mf*; and forte, *f*. The three sound levels are, on the average, 78, 84, and 92 db, respectively, as measured with the General Radio sound level meter with the microphone three inches from the bell of the clarinet. The theory was found to be correct, but it applied more accurately to the chalumeau and the lower middle register than to the higher tones. The higher were shown to be fairly simple in structure, and increasing the intensity above a mezzoforte value seldom introduced any added harmonics. In general, the playing of a *pp* tone always resulted in an almost pure sine curve on the screen of the oscillograph, showing it to consist almost entirely of the fundamental (Figs.

5 and 6). Each register has fairly characteristic tone quality, and the harmonic content becomes simpler from the lowest to the highest pitch.

Graphs of the relative physical intensities of the harmonics, although appealing to the eye, did not lend themselves readily to the drawing of conclusions; for this reason the results were further simplified by the grouping of harmonics, according to relative intensity, into four classifications: strong, medium, weak, and trace. The criterion for classification was: strong, 100 to 50 percent; medium, 50 to 25 percent; weak, 25 to 12.5 percent; and trace, below 12.5 percent. Trace intensities less than 1 percent are not included. These are the percentages of the intensity of the harmonic of maximum intensity. The harmonics were further arranged under each of the headings in the order of decreasing physical intensity.

Table I is an exposition of all tones of the clarinet arranged according to the classification above. The curves are numbered for reference. All tones are forte.

Although the relative physical intensity of the harmonics is much more indicative of what the ear actually hears than the relative amplitudes of the harmonics, it cannot be claimed to represent the sensation set up in the ear. It can be said to represent the physical disturbance near the bell of the clarinet, but the ear response is complicated by a number of factors:

(1) The contributions of most of the harmonics in the weak and trace classes are of minor importance, bordering threshold intensity.

(2) Possible masking effects.

(3) Subjective difference tones which may assume importance where strong, consecutive partials appear.

(4) Variation in threshold intensity with frequency.

The harmonic containing the maximum energy has in many cases been checked for tones of all registers by approximate methods using the General Radio sound analyzer.

Harmonic content for a given tone is by no means the same along the side of the tube and on the axis outside the bell. In fact, in the case of p tones in the high register, the fundamentals are indicated much stronger at one side and higher up the tube than directly outside the bell. Also there seems to be a definite acoustic filtering action due to open tone holes. As would be expected, important variations in quality are seen to result from changes in reed or embouchure.

GENERAL CONCLUSIONS

If one consults the table of results above, one can see that the analyses vary from one tone to the next, even in the same register. This fact might make the drawing of conclusions a little difficult. Therefore, it was decided to take the average intensity for each harmonic throughout each register. These averages were then plotted on the basis of the maximum in each register being 100. These values are the ordinates labeled

TABLE I.

No.	Note	Strong	Medium	Weak	Trace
Low Register					
1	$E_3(D_3)$	1, 5, 3	None	None	8, 6, 2, 4
2	$F_3(D_3\#)$	7, 1	9, 3, 8	None	13, 15, 11, 17, 12, 18, 10, 6, 5
3	$F_3\#(E_3)$	1, 5	7, 3	9	10, 11, 15, 6, 13, 4, 16, 17, 14
4	$G_3(F_3)$	1, 7	18	9, 8, 10	14, 4, 16, 5, 13, 2, 15, 7, 6, 11
5	$G_3\#(F_3\#)$	1	5, 3	None	11, 7, 13, 9, 8, 10, 14, 12, 16, 4, 15
6	$A_3(G_3)$	5, 3, 1	7, 6	None	8, 9, 4, 10, 11, 2, 13
7	$A_3\#(G_3\#)$	1, 7	15	9, 6	8, 5, 16, 3, 2, 11, 13, 14, 18, 17, 10, 4, 12
8	$B_3(A_3)$	3	None	1, 5	9, 6, 7, 8
9	$C_4(A_3\#)$	1	None	None	5, 6, 8, 10, 12, 7, 2, 4
10	$C_4\#(B_3)$	1	3	7, 6	5, 8, 9, 2, 11, 12, 4
11	$D_4(C_4)$	1, 2	None	7, 3	11, 5, 9, 10, 15, 12, 13, 17, 4, 16, 6
12	$D_4\#(C_4\#)$	3	7	5	9, 6, 4, 10, 11, 2, 1, 17
*12*a*	$D_4\#(C_4\#)$	1	3	7	11, 17, 9, 14, 20, 8, 16, 12, 19
13	$E_4(D_4)$	1	7, 3, 5	2, 10, 18, 6	11, 17, 9, 14, 20, 8, 16, 12, 19
14	$F_4(D_4\#)$	1, 8, 9	10, 7	None	3, 5, 11, 12, 6, 4, 2
15	$F_4\#(E_4)$	1, 5	9, 8, 10, 7	6	4, 11, 3, 2
16	$G_4(F_4)$	1, 5	9, 7, 10	11, 3	8, 2, 4
17	$G_4\#(F_4\#)$	8, 1, 9, 5	None	None	4, 3, 11
18	$A_4(G_4)$	1, 8	None	9, 10, 3, 5	6, 11, 12, 2
19	$A_4\#(G_4\#)$	1	6	None	7, 5, 3, 8, 4
Middle Register					
20	$B_4(A_4)$	1	None	None	2, 3, 4
*20*a*	$B_4(A_4)$	1	None	None	3, 2
21	$C_5(A_4\#)$	3, 1	6	5	7, 4, 2
22	$C_5\#(B_4)$	1, 3, 6	2	9, 5, 4, 8	10, 7
23	$D_5(C_5)$	None	None	6, 2, 5, 7	None
24	$D_5\#(C_5\#)$	1	None	3	5, 6
25	$E_5(D_5)$	3	1	5, 2	6, 10
26	$F_5(D_5\#)$	3	None	2, 1, 5	4
27	$F_5\#(E_5)$	3	1, 2, 4	5	6
28	$G_5(F_5)$	1	3	None	8, 4
29	$G_5\#(F_5\#)$	4, 1	2	3	5
30	$A_5(G_5)$	4	None	1	3, 5, 2, 6
31	$A_5\#(G_5\#)$	1	None	4, 7, 6, 3	5, 12, 11, 2, 8
32	$B_5(A_5)$	4	None	3, 2	7
33	$C_6(A_5\#)$	3, 1	2	None	6, 5, 4, 9
High Register					
34	$C_6\#(B_5)$	3, 4	2	None	5, 1, 7, 6, 8
35	$D_6(C_6)$	3, 1	None	6, 5	4, 2, 7
36	$D_6\#(C_6\#)$	2	None	1	3
37	$E_6(D_6)$	1, 2, 4	5	3	7
38	$F_6(D_6\#)$	2	None	None	1, 3, 4
39	$F_6\#(E_6)$	1, 2	None	None	3
40	$G_6(F_6)$	2	None	4	1

* Robert E. McGinnis, at the time first clarinetist of the Philadelphia Symphony Orchestra, produced all tones except 12*a* and 20*a*, which were played by the director of the research with a different clarinet and reed. Comparing 12 and 12*a* or 20 it is seen that the harmonic contents, while not identical, are closely related. Recall that the percent harmonic content changes readily with the loudness.

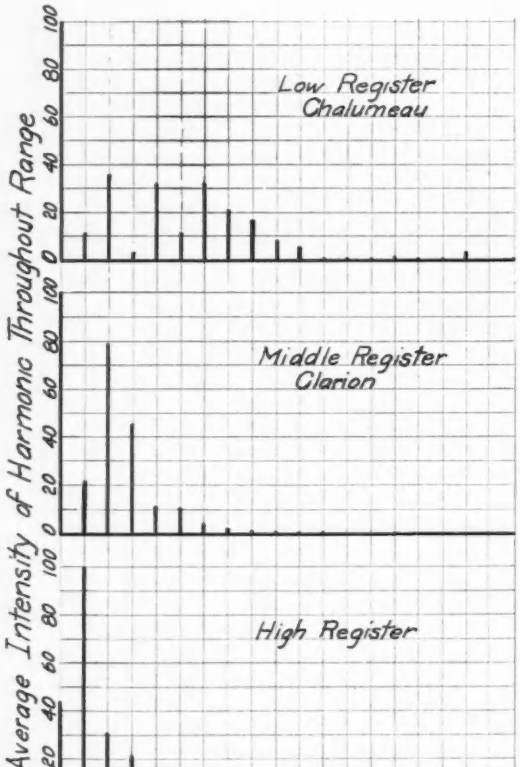


FIG. 7. Average harmonic content for each of the three registers.

"Average intensity of harmonic throughout range" in Fig. 7. The forte tone is always referred to unless otherwise stated. The chalumeau or low register is characterized by:

(1) The fundamental has, on the average, one-third of the total intensity and is not absent in any tone. The unique tone of the clarinet, often described as a reedy or hollow quality, is present to the highest degree in this register, becoming less noticeable in the middle register and being absent entirely in the high register. This unique quality appears to be due to relatively strong odd partials resulting in a hollow harmonic structure, often with a spread of several harmonics between the strong, odd ones.

(2) The lower odd harmonics (1st, 3rd, 5th, and 7th) are usually present and of considerable importance. The 9th occasionally replaces one of this group.

(3) The lower even harmonics (2nd, 4th, 6th and sometimes 8th) are generally unimportant. Of these, the 8th is most important, especially in the so-called throat tones (Nos. 17, 18, and 19), the highest pitches in this register. Performers consider No. 19 as sensitive and rather of inferior quality.

(4) In the higher harmonics, above the 9th, the even ones may appear as often and as prominently as the odd.

(5) Of the total intensity, about 78 percent is in the odd harmonics.

(6) Decreasing the intensity from forte to pianissimo results in simplification of the harmonic structure of the tones, until, finally, only the fundamental and one or two very weak, low, harmonics remain.

The clarion or middle register is characterized as follows:

(1) The fundamental averages slightly more intense than in the low register, i.e., a little more than one-third of the total intensity.

(2) In B_4 (A_4), the tuning note in orchestra, the fundamental is the strongest of any tone in the entire pitch range of the clarinet.

(3) The second harmonic is stronger and the fourth is much stronger than in the low register. Thus the hollow harmonic structure is less effective than in the low register and the hollow, reedy quality of tone is noticeably less in evidence.

(4) Almost all the intensity, about 96 percent, is contained in the first six harmonics. No harmonics above the tenth are of appreciable importance.

(5) Changing the intensity from forte to mezzo-forte causes little change in the wave form.

(6) Playing the tones pianissimo results in simpler patterns.

The high register is characterized as follows:

(1) The fundamental is much weaker than in both the other registers.

(2) The second harmonic is by far the strongest and only in this register is this the case.

(3) Almost all the intensity, about 99 percent, is contained in the first six harmonics. No harmonics above the seventh are of appreciable importance in any tone.

(4) There is no hollow harmonic structure, and the hollow, reedy quality which particularly characterizes the clarinet has been lost.

(5) The effect of variations in wave form with intensity is similar to that of the middle register.

Throughout the total clarinet range the most intense overtone is the second, i.e., the third harmonic. It contains, on the average, 18.3 percent of the total energy.

Concerning the tuning of the clarinet, it may be of interest to players to know that it is possible to obtain strong resonance of the 3rd harmonic of E_3 (D_3) with the orchestra tuning bar of 440 cycles per second. For tuning a clarinet with B_4 (A_4), a mezzoforte tone is better than a forte tone because the former contains a decidedly stronger fundamental.

If the clarinet were to behave like a closed tube, only odd harmonics would be present to any considerable degree, especially in the low register where the register key is not used. The even harmonics would either be absent or else be present to only an unimportant extent. As can be seen, the 2nd, 4th, 6th, and 8th and sometimes the 10th are present even if generally weak in the low register, and the 4th is of considerable importance in the middle register. In fact the higher even harmonics may be present to the same extent that the odd ones are. In the high register, an even harmonic, the 2nd, is most important. It seems, then, that the clarinet tube acts as a closed pipe only to a limited extent, and more so in the low register than in the other two.

CONCERNING QUALITY

The quality of the chalumeau is unique in the orchestra and is not even approximated by any other instrument. It is considered by many persons to be more beautiful than that of the other registers of the clarinet. This unique quality appears to be due to the following causes: (1) Absence or weakness of the 2nd, 4th, and 6th harmonics: (2) the relative loudness of the 1st, 3rd, 5th, and 7th harmonics. This creates a hollow harmonic structure which causes a hollow reedy quality. This quality is present to only a limited extent in the middle register and is entirely absent in the high register. For pianissimo playing in the low register, where we have a strong fundamental without the hollow harmonic structure, the unique chalumeau quality is lost. When we examine all these facts, the reasons presented for the peculiar chalumeau quality seem to be quite plausible. A fine example of this quality can be found at the beginning of the first movement of Tschaikowsky's "Fifth Symphony." Excellent examples of the quality of all three registers are to be found in the clarinet cadenzas of Liszt's "Second Hungarian Rhapsody." Comparisons bearing on quality are as follows: (1) The middle and high registers have no important harmonics above the 10th. (2) The distribution of the total energy between the even and the odd harmonics and also the distribution for the first eight harmonics for each register are given in Table II.

TABLE II.

	Low %	Medium %	High %
Total energy			
Odd partials	77.8	70.8	40.0
Even partials	22.2	29.2	60.0
First 8 partials only			
Odd partials	68.1	70.0	40.0
Even partials	16.3	28.0	60.0

Thanks are due to Mr. John A. Weir for his work on early analyses, to Mr. H. H. Kramer for his construction of the harmonic analyzer, and to the Committee on Research for necessary appropriations.

Acoustical Society News

C. R. Hanna Receives Presidential Citation

Members of the Acoustical Society were intensely pleased on December 10th to learn, through the radio and newspapers, that C. R. Hanna, an active member of the Acoustical Society and one-time Vice President, had been called to Washington to receive directly from President Roosevelt a citation of "individual production merit" for his work in developing a device that immensely increased the effectiveness of American tanks. Presentation of the award at the White House to Mr. Hanna and five others was scheduled as the highlight of a day of official receptions, entertainment, and other activities. Signed by Donald Nelson, Chief of the War Production Board, and countersigned by President Roosevelt, Mr. Hanna's citation read: "In recognition of his initiative and patriotism, be it known that Clinton R. Hanna is hereby cited for his meritorious contribution to the war production drive." Mr. Hanna is 43 years old and Manager of the Electro-Mechanical Department of the Westinghouse Research Laboratories.

The Acoustical Society congratulates Mr. Hanna on the receipt of this well-earned honor and recognition.

Clinton R. Hanna

Secretary Waterfall

Secretary Wallace Waterfall is now on leave of absence from the Celotex Corporation and is associated with the Office of Scientific Research and Development in New York. He will, however, continue to be active in the Acoustical Society and the Acoustical Materials Association. Mail for the Secretary should be sent to 120 South La Salle Street, Chicago, as in the past.

New Members

James Norton Brennan
518 East 83rd Street
New York, New York
Research Technician
G. R. Kinney Company, Inc.
2 Park Avenue
New York, New York

Francis Pettit Bundy
Harvard University
Cambridge, Massachusetts
Research Physicist

Frank Dawson Hallworth
31 Knowles Avenue
Middletown, Connecticut
Technical Physicist
Pratt & Whitney Aircraft
East Hartford, Connecticut

Henry Peter Meisinger
3005 Nelson Place, S. E.
Washington, D. C.
Chief Engineer
United States Recording Co.
1221 Vermont Avenue, N.W.
Washington, D. C.

Kenneth Lee Pike
1522 Rackham Building
Ann Arbor, Michigan
Linguist

Erratum: Mr. Eliot W. Higgins was previously erroneously listed as deceased, having merely dropped his membership in the Society.

Fellows	166
Members	695
Total membership	861

Current Publications on Acoustics

F. A. FIRESTONE
147 Randall Laboratory, University of Michigan, Ann Arbor, Michigan

Reviews of Contemporary Papers on Acoustics

MEMBERS who have occasion to translate important papers from foreign journals will be doing a real service to those members who do not read the foreign languages easily, if they will prepare a review of such articles for publication in this section.

These reviews should be of the nature of a lengthy abstract (500 to 1500 words) rather than a critique or appraisal, and should attempt to set forth in this limited space as much of the original author's contribution as possible. One or two figures may be included if desired.

Contribution to the Acoustics of Radio Studios. W. FURRER, Swiss Archives for Applied Science and Technique **8**, 77–85, 99–109, 143–152 (1942). The present work is a condensation and evaluation of the experiences which were accumulated from the acoustical formation of new radio studio buildings erected in Switzerland between 1937 and 1940. This includes buildings in Lugano, Zurich, Basle, and Geneva which altogether have cost over 4 million Swiss francs.

Volumes of music studios are discussed in the first section. It is shown that three comparatively narrowly limited categories of music studios are sufficient for all practical questions as sources of sound: large studios, 2000 to 5000 cubic meters; medium studios, 600 to 1000 cubic meters; small studios, 200 to 300 cubic meters.

In the second section, the optimum reverberation time for studios is discussed. It is first pointed out that theories, well-known in the literature, cannot satisfy when they are used in attempts to create conditions of optimum reverberation time by theoretical deliberations. It appears questionable whether this method ever can be successful. Musical perception, on which it depends in the final analysis, is something so subjective that one is forced to evaluate statistically the most comprehensive possible material of subjective judgments, in order thus to make a bridge to physical acoustics. In this sense, the measure of reverberation of rooms, preferably concert halls, whose acoustics are recognized as good, provides the natural medium for arriving at incontestable clues to optimum reverberation time. The evaluation of such measures shows that the reverberation times of concert halls are, so to speak, exclusively determined by the audience and that the construction of the room plays only a secondary role; this may explain the fact that the values found by numerous authors from the most diversified places agree well.

The question then arises whether these conditions hold good directly for radio studios where the listener is dependent on the transmission over a single channel rather than the direct hearing with two ears. In spite of theoretical considerations to the contrary numerous tests proved that this is, nevertheless, the case. Thus, in regard to reverberation, large studios can be dimensioned exactly as corresponding concert halls.

For the medium and smaller studios, other aspects are decisive so that the following optimum reverberation times result (at 1000 cycles): large studios, 2000–5000 cubic meters: 1.35–1.5 s; medium studios, 600–1000 cubic meters: 1.0 s; small studios, 200–300 cubic meters: 0.6 s.

The influence of the reproduction room must be taken into account with the small studios. The resulting reverberation time of the two electrically connected rooms is calculated.

Regarding the *frequency characteristic of the reverberation time*, as early as 1930 W. A. MacNair advanced the claim that the subjectively experienced reverberation time must be independent of frequency, whence, in consideration of the frequency-dependent ear sensitivity, an increase of the effective existing reverberation time for low frequencies resulted. A comparison of the frequency characteristic arrived at in this fashion with the frequency characteristic of audience sound absorption results, as is well known, in an amazingly close resemblance. Therefore, it is confirmed in a second way that the reverberation time of a good concert hall is determined mainly through the natural factor of the audience.

It was possible to prove experimentally that the same considerations also are valid for radio studios, so that, for music studios at 100 cycles the resulting reverberation time is 1.5 to 2 times *longer* than at 1000 cycles.

For the dimensioning of studios for speech other aspects are decisive. Differentiation is made between "talks" studios of 30–50 cubic meters volume and studios for dramatic production of 150–250 cubic meters. Above all, the intelligibility of the spoken word is important here, for which, according to V. O. Knudsen, an extremely high sound absorption is desirable. Since high sound absorption, particularly at low frequencies demands a great expense and too-strong damping is undesirable for other reasons as well, the question here is that of minimal expense for sound absorption materials. These considerations as well as numerous trials led to the values given in Table I.

In a third section, the *theories and investigations of reverberation time* are treated. This part begins with the idea that none of the well-known theories of reverberation is entirely satisfactory and that there are at hand no exhaustive reports about the scope of practical application or the exactitude to be expected. The building of the

TABLE I.

Frequency	Maximum reverberation time "Talks" studios	Studios for dramatic production
100 cycles	0.6 s	0.8 s
200–2000 cycles	0.4 s	0.6 s

radio studios, therefore, offered a welcome opportunity to make experimental trials in this direction.

The reverberation measuring technique was based on a high speed level recorder. It was measured as usual with frequency modulated tones (warble tones) whereby the evaluation of quantity and circular frequency of the frequency changes is discussed. Besides this method, attempts by the method of measuring in stationary condition, indicated by F. V. Hunt, are also described, the employment of which, however, presented considerable practical difficulties.

A first set of results aimed at the determination of *variation of reverberation time due to position*. In 11 rooms, whose volumes ranged from 40 to 4500 cubic meters and whose reverberation times lay between 0.17 and 4.3 s, reverberation times were measured at 100 positions in each with frequencies of 100, 800, and 4800 cycles. Thereby it was shown that the *dispersion of reverberation time due to position in an acoustically good room represents a Gaussian distribution.*

Figure 1 shows the result of such a series of recordings, entered in a probability projection.

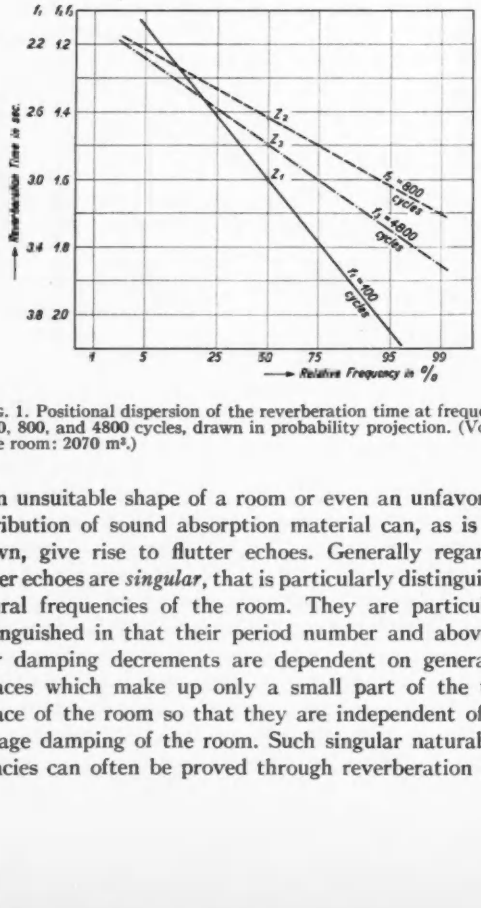


FIG. 1. Positional dispersion of the reverberation time at frequencies of 100, 800, and 4800 cycles, drawn in probability projection. (Volume of the room: 2070 m³.)

An unsuitable shape of a room or even an unfavorable distribution of sound absorption material can, as is well known, give rise to flutter echoes. Generally regarded, flutter echoes are *singular*, that is particularly distinguished natural frequencies of the room. They are particularly distinguished in that their period number and above all their damping decrements are dependent on generating surfaces which make up only a small part of the total surface of the room so that they are independent of the average damping of the room. Such singular natural frequencies can often be proved through reverberation time

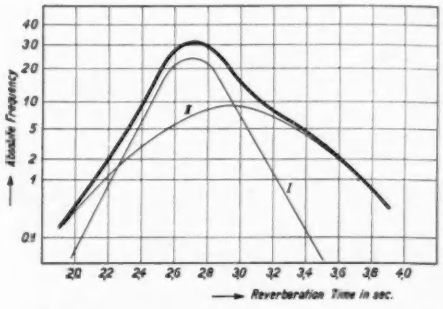


FIG. 2. Analysis of an irregular curve of absolute frequency (due to flutter echoes) in two Gaussian frequency curves.

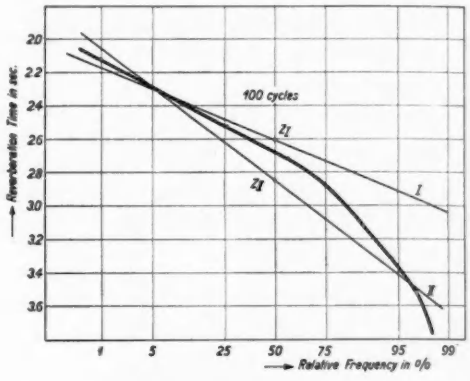


FIG. 3. Irregular curve of relative frequency, analyzed in two Gaussian curves. (Probability projection.)

recordings which intersect the questionable zone of the room. In this zone, then, very typical reverberation recordings are obtained. It has also been shown further, that, in rooms showing singular natural frequencies, the dispersion dependent on position no longer obeys the Gaussian distribution. This indication is very sensitive; the Gaussian distribution is plainly disturbed even if the responsible singular natural frequencies cannot be detected at all by any other method.

Figure 2 shows an example of this. In such a case, an attempt can be made to resolve graphically the curve of the absolute frequency into two or more Gaussian frequency curves. (See Fig. 3.) Thereby the corresponding straight lines can be drawn in the probability projection. Hence it follows that a room with singular natural frequencies no longer represents a unified collective, but is composed of two or more collectives. From their number and the corresponding central value, it is often possible to arrive at the way the singular natural frequencies came into being.

The positional dispersion of the reverberation time and its evaluation thus gives a new criterion for the judgment of the acoustics of a room which involves the shape of the room and the distribution in it of sound absorption. This is all the more worth while, since the simple theories of reverberation cannot take into account these two factors. Formerly, it was only through more or less approximate geometrical speculations that anything could be stated about it.

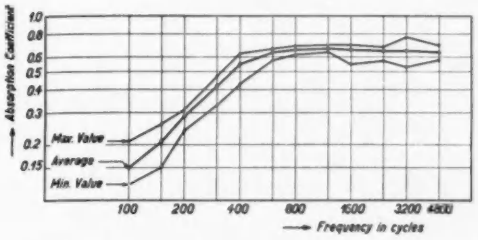


FIG. 4. Absorption coefficient of glass wool, measured in different rooms.

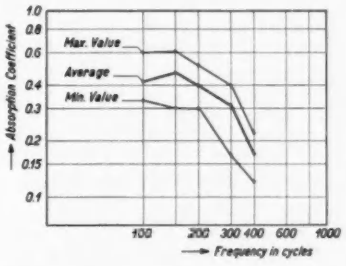


FIG. 5. Absorption coefficient of plywood resonance board, measured in different rooms.

Sound absorption materials: It was shown that, on principle, it is not possible to find a simple homogeneous material, which shows an absorption whose frequency characteristic corresponds to that of the desirable reverberation time. Two different materials were used namely, glass wool and plywood resonance board. The glass wool was covered over in the ordinary way with punched sheets. Thanks to these standardized absorption materials, it was possible to measure the absorption in a number of rooms of different volumes and shapes as well as with testing surfaces of various sizes and variously distributed.

The results obtained in this fashion are shown in Figs. 4 and 5. For plywood, only the lower frequency range up to 400 cycles could be evaluated since its absorption is too small at the higher frequencies. In calculation of the exhibited absorption from the reverberation times, it was plainly shown that the Millington formula gives the results most nearly corresponding to reality. An arithmetical addition of the absorbing surfaces, according to Sabine or Eyring, led to no usable results. Figures 4 and 5 permit recognition of the expected deviations: plus or minus 20 percent from 100 to 400 cycles (plywood plus or minus 30 percent due to larger material differences), plus or minus 10 percent from 400 to 4800 cycles. These deviations must also be taken into account in the calculation of reverberation times.

In view of the complexity of the phenomenon of reverberation and of the very large scope encompassed, these deviations are relatively slight: a fact which is also indirectly a demonstration of the value of the classical reverberation method for measurement of sound absorption. It is indeed well known that this method, in spite of its simplicity in principle, actually never did produce entirely significant results. Therefore, attempts were made to obtain in the reverberation chamber as well, the absorption value of a given material (glass wool) obtained in various studio rooms. Figure 6 shows the result: When

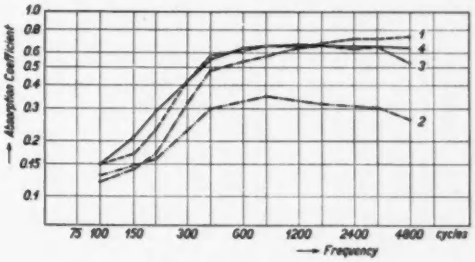


FIG. 6. Absorption coefficient of glass wool, measured in the reverberation chamber (volume 40 m³) under different conditions: (1) Three test samples, 3 m³ each; (2) one test sample, 9 m³; (3) one test sample, 3 m³; (4) average curve from Fig. 4.

three test samples are laid on three non-parallel walls and calculated with the Millington formula, then the two curves agree very satisfactorily. Finally, an explanation is given why a single test sample in a rectangular chamber must produce too low absorption values mainly at the medium and high frequencies, not at the low ones.

At the close of the work, there is a list of practical conclusions, particularly those concerning the shape of the rooms and the distribution of the absorption material. The measured reverberation curves of 15 studios are shown as well as individual pictures of typical examples.

References to Contemporary Papers on Acoustics

MOST of the titles of papers appearing in other languages than English have been translated. Abstracts in English of many foreign papers have appeared or soon will appear in Science Abstracts, Section A. Where references are made to Science Abstracts, the reference is to the volume number and abstract number. The abbreviations of the names of journals are those used in Science Abstracts and can be found in any annual index to those abstracts.

The numbers appearing at the head of each entry are the numbers which identify the subject headings in the Cumulative Index of this journal issued in November, 1939. The same Classification of Subjects can be found in the index to Volume 14, this issue.

Compiled with the generous assistance of Samuel Sass, Physics Librarian, University of Michigan.

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2. Architectural Acoustics

2.1 **Sound in the Theater.** Harold Burris-Meyer. Report No. 6. Mimeographed book of 111 pages published by the author.

2.1 **Selected Problems in Architectural Acoustics.** M. Rettinger. Proc. I.R.E. **31**, 18–22 (Jan. 1943).

2.2 **Contribution to the Acoustics of Radio Studios. Parts 1 and 3.** W. Furrer. Schweizer Arch. f. angew. Wiss. u. Tech. **8**, 77–85, 143–152 (1942).

2.9 **Sound-Proofing Needed in Engine Testing Laboratories.** Scientific American **168**, 41 (Jan. 1943).

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3.1 **Book Review: Physik und Technik des Tonfilms.** H. Lichte and A. Narath. J. Appl. Phys. **13**, 746 (Dec. 1942).

4. Ear and Hearing

4.1 **The Role of Audible Frequencies in the Perception of Obstacles by the Blind.** M. Cotzin. Psychol. Bull. **39**, 503–504 (1942).

4.1 **Hearing, The Determining Factor for High-Fidelity Transmission.** Harvey Fletcher. Bell Sys. Tech. J. (1942).

4.1 **Avoidance of Obstacles by Flying Bats: Spallanzani's Ideas (1794) and Later Theories.** R. Galambos. Isis **34**, Part 2, 132–140 (1942).

4.1 **Observations on Acoustic Trauma in War and in Peace.** H. B. Perlman. Ann. Otol. Rhinol. Laryngol. **51**, 541–544 (1942).

4.2 **Development of the Human Stapes.** B. J. Anson. Ann. Otol. Rhinol. Laryngol. **51**, 449–451 (1942).

4.2 **Acoustic Movements of the Human Sound Conduction Apparatus.** H. F. Kobrak. Ann. Otol. Rhinol. Laryngol. **51**, 162–163 (1942).

4.3 **Binaural Interaction and the Nature of Pitch Perception.** W. R. Thurlow. Psych. Bull. **59**, 503 (1942).

4.4 For Papers on Deafness, see Volta Review.

4.4 **Growing Deaf and Learning Lip Reading.** E. B. Love. Volta Rev. **45**, 36–38 (Jan. 1943).

4.4 **Residual Hearing.** C. S. Nash. Laryngoscope **52**, 577–589 (1942).

4.4 **On Estimating the Percentage Loss of Useful Hearing.** P. E. Sabine. Trans. Am. Acad. Ophthal. Otolaryng. **46**, 179–196 (1942).

4.4 **Research Possibilities with the Deaf.** A. Zeckel. Am. Ann. Deaf **87**, 173–191 (1942).

4.5 **Hearing Aids: The Medical Aspect; A Case for Cooperation.** C. M. R. Balbi. Wireless World **48**, 201 (Sept. 1942).

4.6 **Hearing and Vision of American Fliers.** Science **97**, No. 2510, Suppl. 10 (Feb. 5, 1943).

4.9 **Absolute Pitch.** Ll. S. Lloyd. The Musical Times. No. 1198, 379 (Dec. 1942).

4.10 **An Alternate Approach to the Mathematical Biophysics of Perception of Combinations of Musical Tones.** N. Rashevsky. Bull. Math. Biophys. **4**, 89–90 (June, 1942); Sci. Abs. **A45**, 2556 (1942).

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5.7 **New Reference Frequency Equipment.** V. J. Weber. Bell Lab. Rec. **21**, 73–76 (Nov. 1942).

5.8 **The Effect of a Plane Screen on the Output of a Loudspeaker.** L. L. Myasnikov. J. Tech. Phys. (U.S.S.R.) **10**, 1372–1381 (1940); Wireless Engineer **19**, 3279A (1942).

5.10 **One-Dimensional and Two-Dimensional Propagation of Sound Waves in Water, in Tubes, and Tanks.** K. Tamm. Alta Frequenza **11**, 251–252 (May, 1942).

5.13 **Sound in the Theater.** Harold Burris-Meyer. Report No. 6. Mimeographed book of 111 pages published by the author.

5.13 **"Commercial Sound" Enlists; the Microphone and the Loudspeaker Join in the War Effort to Increase Efficiency of Operations.** G. R. Ewald. Scientific American **168**, 70–72 (Feb. 1943).

5.13 **Hearing, The Determining Factor for High-Fidelity Transmission.** Harvey Fletcher, Bell Sys. Tech. J. (1942).

5.15 **A Spread-Scale Recorder.** O. D. Engstrom. Bell Lab. Rec. **21**, 66–69 (Nov. 1942).

5.16 **Hearing, The Determining Factor for High-Fidelity Transmission.** Harvey Fletcher. Bell Sys. Tech. J. (1942).

5.16 **The Measurement of Transcription-Turntable Speed Variation.** H. E. Roys. Proc. I.R.E. **31**, 52 (Feb. 1943)

5.16 **The Reduction of Record Noise by Pick-Up Design.** A. D. BURT. Electronics **16**, No. 1, 90–93, 198–99 (Jan. 1943).

5.16 **Technical Basis of Sound Reproduction.** Nature **150**, 629–630 (Nov. 28, 1942).

5.16 **How Recordings are Made.** No. 5—**Tests and Trouble-shooting.** C. B. DE SOTO. QST **26**, 51–55 (Dec. 1942).

5.16 **A Demonstration of Radio Fundamentals and Speech Quality.** L. W. JONES. Amer. J. Phys. **10**, 330–331 (Dec. 1942).

5.16 **Book Review: Physik und Technik des Tonfilms.** H. LICHTE AND A. NARATH. J. Appl. Phys. **13**, 746 (Dec. 1942).

5.17 **Sound-Proof Panels Can be Added to Old Telephone Booths.** Scientific American **167**, 283–284 (Dec. 1942).

5.19 **On the Theory of the Mechanism of Vibration of a Tuning Fork.** K. BASZEL. Funktech. Monatshefte. No. 10, 145–148 (Oct. 1941).

5.51 **Hearing, The Determining Factor for High-Fidelity Transmission.** HARVEY FLETCHER. Bell Sys. Tech. J. (1942).

5.51 **Contribution to the Acoustics of Radio Studios. Parts 1 and 3.** W. FURRER. Schweizer Arch. f. angew. Wiss. u. Tech. **8**, 77–85, 143–152 (1942).

5.51 **Contemporary Problems in Television Sound.** C. L. TOWNSEND. Proc. I.R.E. **31**, 3–7 (Jan. 1943).

6. MUSICAL INSTRUMENTS AND MUSIC

6.1 **Book Review: Acoustics of Music.** W. T. BARTHOLOMEW. Proc. I.R.E. **31**, 42 (Jan. 1943).

6.1 **Hearing, The Determining Factor for High-Fidelity Transmission.** HARVEY FLETCHER. Bell Sys. Tech. J. (1942).

6.1 **Color and Music.** V. G. W. HARRISON. J. Roy. Soc. Arts **90**, 609–612 (Aug. 7, 1942).

6.1 **Modern Science and Musical Theory.** LL. S. LLOYD. J. Roy. Soc. Arts **90**, 581–593 (Aug. 7, 1942).

6.1 **Seventeenth-Century English Research in Acoustics.** LL. S. LLOYD. Musical Times **84**, 29 (Jan. 1943).

6.7 **On the Frequency Characteristic Curves of Violins.** H. MEINEL. Alta Frequenza **11**, 175–176 (Mar./Apr. 1942).

7. NOISE

7.1 **The Noise Primer. Parts 1 and 2.** H. H. SCOTT. Gen. Radio Exper. **17**, No. 8, 2–6 (Jan. 1943).

7.7 **Sound-Proofing Needed in Engine Testing Laboratories.** Scientific American **168**, 41 (Jan. 1943).

7.7 **The Measurement of the "Vortex Sound" Spectra of Rotating Rods, Plates, and Airscrew Models.** E. A. NEPOMNYASHCHI. J. Tech. Phys. (U.S.S.R.) **10**, 1800–1810 (1940) (in Russian); Wireless Engineer **19**, 3616A (1942).

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9.1 **Radiation Pattern of the Human Voice.** Nature **150**, 583 (Nov. 14, 1942).

9.1 **Radiation Pattern of the Human Voice.** D. W. FARNSWORTH. Sci. Mon. **55**, 139–143 (Aug. 1942).

9.1 **Speech in a Hearing Aid Class.** Association Committee Report. Volta Rev. **45**, 7–11 (Jan. 1943).

9.1 **Vocal Timbre in Its Immediate and Successive Aspects.** O. J. BORCHERS. Proc. Music Teach. Nat. Ass. 346–358 (1942).

9.1 **Avoidance of Obstacles by Flying Bats: Spallanzani's Ideas (1794) and Later Theories.** R. GALAMBOS. Isis **34**, Part 2, 132–140 (1942).

9.3 **Judging Intelligibility of Speech.** CLARENCE V. HUDGINS. Volta Rev. **45**, 5–6 (Jan. 1943).

10. SUPERSONICS (ULTRASONICS)

10.3 **Signal Generators with 1 Kilowatt Output: Primarily for Tests on Supersonic Generators, Etc.** H. NITSCHE. Hochfrequenztechnik u. Elektroakustik **59**, 138–143 (May, 1942).

10.5 **Adiabatic Compressibilities of Oils (Determined from the Ultrasonic Velocities in the Oils).** SREE. J. Mysore Univ. **2**, 13, 95–97 (1942); Sci. Abs. **A45**, 2551 (1942).

10.6 **Théorie de l'influence des ondes ultra-sonores sur la diffraction des rayons X par les cristaux.** J. WEIGLE AND K. BLEULER. Helv. Phys. Acta **15**, 445–454 (1942).

11. WAVES AND VIBRATIONS

11.3 **Velocity of Sound in Liquids and Molecular Volume.** M. R. RAO. J. Mysore Univ. **2**, 12, 89–93 (1942); Sci. Abs. **A45**, 2552 (1942).

11.6 **The Attenuation of Sound in Absorbing Tubes.** W. WILLMS. Alta Frequenza **11**, 252–254 (May, 1942).

11.7 **On the Theory of the Mechanism of Vibration of a Tuning Fork.** K. BÁSZEL. Funktech. Monatshefte No. **10**, 145–148 (Oct. 1941).

11.7 **On the Reflection of a Spherical Sound Pulse by a Parabolic Mirror.** F. G. FRIEDLANDER. Proc. Camb. Phil. Soc. **38**, 383–393 (Nov. 1942).

11.7 **On the Solutions of the Wave Equation with Discontinuous Derivatives.** F. G. FRIEDLANDER. Proc. Camb. Phil. Soc. **38**, 378–382 (Nov. 1942).

11.7 **On a Generalization of Kirchhoff's Theory of Transverse Plate Vibrations in the Vibration Problem of Steam Turbine Disks.** I. MALKIN. J. Franklin Inst. **234**, 431–452 (Nov. 1942).

11.7 **Model Tests of Two Types of Vibration Dampers.** C. A. MEYER AND H. B. SALDIN. J. Appl. Mech. **9**, A59–A64 (June, 1942); Sci. Abs. **A45**, 2553 (1942).

11.7 **The Measurement of the "Vortex Sound" Spectra of Rotating Rods, Plates, and Airscrew Models.** E. A. NEPOMNYASHCHI. J. Tech. Phys. (U.S.S.R.) **10**, 1800–1810 (1940) (in Russian); Wireless Engineer **19**, 3616A (1942).

11.7 **Elastic Waves and Vibrations of Thin Rods.** JOHN PRESCOTT. Phil. Mag. **33**, 703–754 (Oct. 1942).

12. GENERAL, UNCLASSIFIED

Sound in the Theater. HAROLD BURRIS-MEYER. Report No. 6. Mimeographed book of 111 pages published by the author.

Review of Acoustical Patents

ROBERT W. YOUNG
C. G. Conn, Ltd., Elkhart, Indiana

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The decimal numbers appearing before titles are the numbers which identify the subject headings in the Cumulative Index of this journal issued in November, 1939. The Patent Office classification given in parentheses with each patent entry is outlined in the "Manual of Classification of Patents" which is obtainable from the Superintendent of Documents for $1.50.

Unless otherwise indicated, patents listed have been issued by the United States Patent Office.

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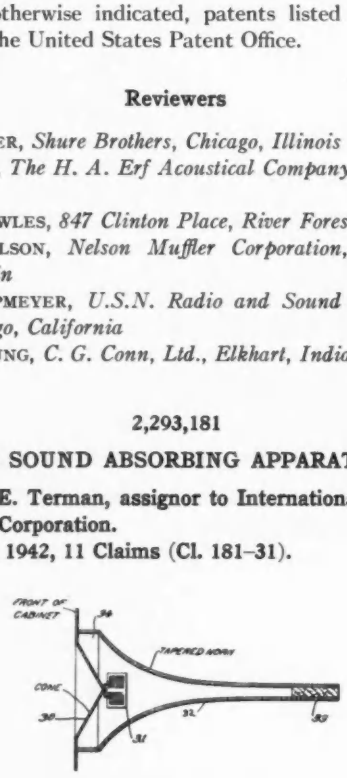
2,293,181

5.8 SOUND ABSORBING APPARATUS

Frederick E. Terman, assignor to International Standard Electric Corporation.
August 18, 1942, 11 Claims (Cl. 181–31).

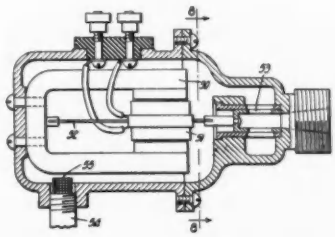


Describes the use of an exponential or a modified exponential horn as an acoustical terminating resistance for loudspeakers, etc. When the throat of the horn is provided with a plug of sound absorbing material, the mouth of the horn appears as a resistance.—B.B.B.

2,288,607

5.8 PNEUMATICALLY OPERATED LOUDSPEAKER

Edward F. Chandler, assignor of one-half to Stewart P. Foltz.
July 7, 1942, 10 Claims (Cl. 179–108).

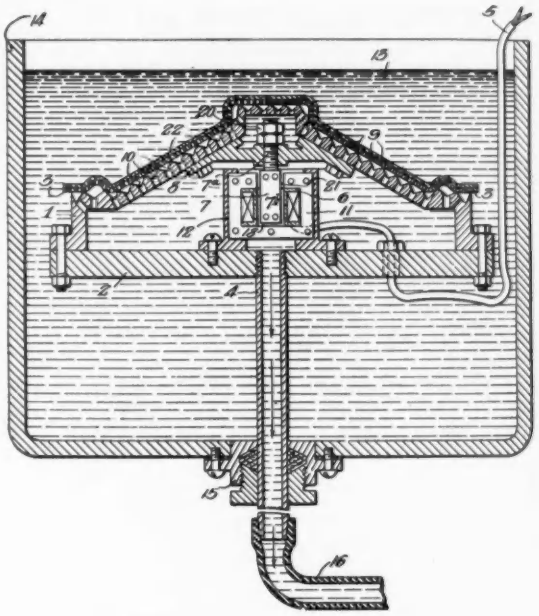


In this pneumatic speaker modulation of the air supplied is accomplished by a signal controlled rotary sleeve valve with a multiplicity of parts. Lighter moving parts, less distortion and hiss, and greater load capacity are claimed.

2,288,832

5.8 FIBROUS ACOUSTIC DIAPHRAGM

Victor T. Pare, assignor to Radio Corporation of America.
July 7, 1942, 2 Claims (Cl. 181–32).

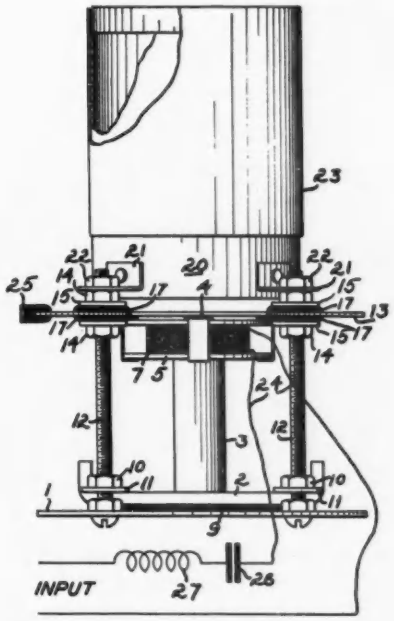


This patent describes means of producing compactly felted loudspeaker cones by a vibrating former. The claims cover only the final product, and not the means.

2,291,108

5.8 SELECTIVE ELECTRO-ACOUSTICAL TRANSDUCER

Edward M. Sargent and Lyndon C. Rayment.
July 28, 1942, 4 Claims (Cl. 178–98).



For cutting through QRM and static in ICW reception this loudspeaker has been made selective by two sharply tuned elements. A loosely supported thick diaphram, driven by a conventional motor, works into a tube of adjustable length. Because of the loose coupling and low decrement, blurring of fast signals occurs, and is reduced by adjustable damping tabs gripping the edge of the diaphragm.

2,291,459

5.8 LOUDSPEAKER

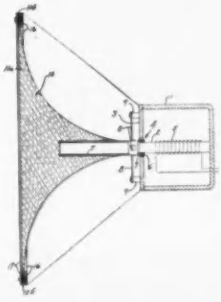
Stewart P. Foltz and Raymond B. Peterson.
July 28, 1942, 3 Claims (Cl. 179–110).

This rotary sleeve valve pneumatic speaker is actuated by a twister type piezoelectric crystal. The valve is that of Chandler, patent 2,288,607.

2,297,218

5.8 LOUDSPEAKER

Hans E. Henrich and Oskar Vierling, Berlin, Germany; vested in the Alien Property Custodian.
September 29, 1942, 15 Claims (Cl. 181–32).

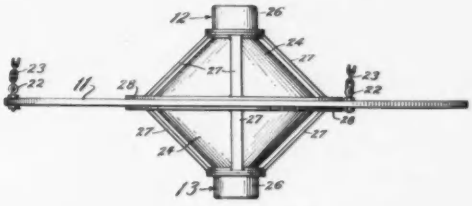


The radiating surface of this loudspeaker is the base of solid of revolution whose contour is approximately exponential. The light cellular material used in its construction has high losses for wave motion; more uniform response in the range 30–10,000 c.p.s. is claimed.

2,297,972

5.8 SOUND REPRODUCING DEVICE

Bert E. Mills, assignor to Mills Novelty Company.
October 6, 1942, 4 Claims (Cl. 179–116).

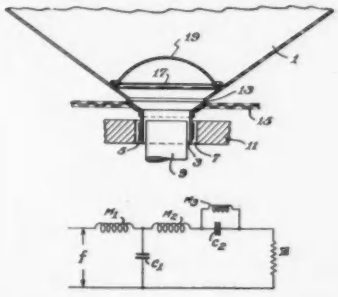


This device is essentially two direct radiator speakers face to face and separated by a small common baffle. The cones move together to approximate the effect of an oscillating sphere; a spherical distribution of sound is claimed.

2,303,989

5.8 SIGNAL TRANSLATING APPARATUS

David H. Cunningham, assignor to Radio Corporation of America.
December 1, 1942, 6 Claims (Cl. 179–115.5).

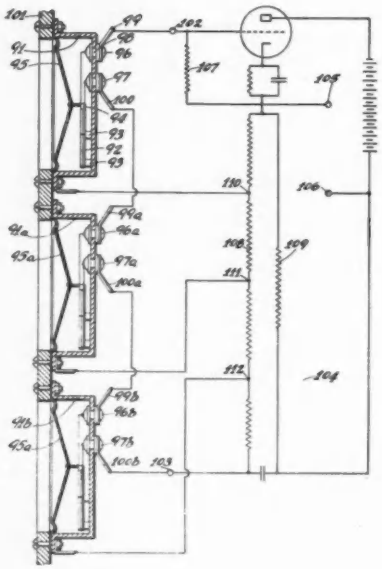


Sharp acoustic cut-off is achieved, in the loudspeaker described in this patent, by means of dust cap having distributed mass and compliance to form a sharply resonant trap circuit. Also present are previously disclosed filter elements in the form of a metal ring (over which the cap is placed) and a compliance between this and the voice coil.

2,282,319

5.9 LEAKAGE REDUCING MEANS

Walter J. Brown, assignor to The Brush Development Company.
May 12, 1942, 24 Claims (Cl. 179–1).

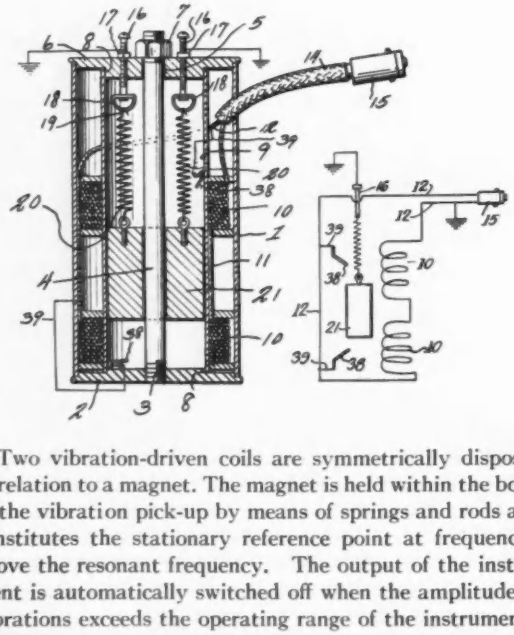


Means for reducing the surface leakage in piezoelectric microphones by electrically connecting various leakage surfaces of the microphone to the points in the amplifier circuit where the voltage is very nearly equal to and in phase with the voltage generated in the microphone.—B.B.B.

2,286,897

5.9 VIBRATION PICK-UP

Philip J. Costa and George E. Holback.
June 16, 1942, 5 Claims (Cl. 171–209).

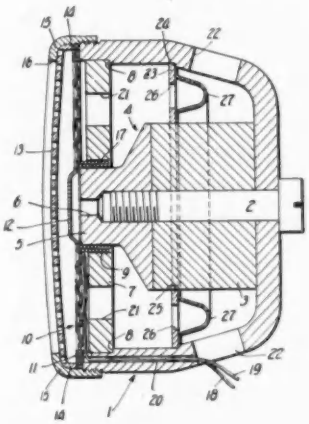


Two vibration-driven coils are symmetrically disposed in relation to a magnet. The magnet is held within the body of the vibration pick-up by means of springs and rods and constitutes the stationary reference point at frequencies above the resonant frequency. The output of the instrument is automatically switched off when the amplitude of vibrations exceeds the operating range of the instrument.—B.B.B.

2,293,078

5.9 MICROPHONE

Barton A. Proctor, assignor to B. A. Proctor Company, Inc.
August 18, 1942, 5 Claims (Cl. 179–115.5).

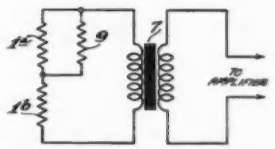


Mechanical structure comprising in combination a diaphragm having a flexible annulus and provided with a voice coil, and a magnetic structure of the conventional type, with apertures furnishing communication between the interior of said structure and the atmosphere, and a flexible rubber diaphragm to seal out dirt and moisture.—B.B.B.

2,295,376

5.9 ELECTROACOUSTICAL APPARATUS

Leslie J. Anderson, assignor to Radio Corporation of America.
September 8, 1942, 9 Claims (Cl. 179–139).



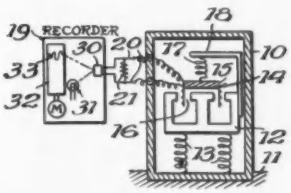
Describes means for balancing the outputs of the velocity-operated ribbon **1a** and the pressure-operated ribbon **1b** in a unidirectional microphone by means of a shunting resistance **9** or by means of two impedance matching transformers. This results in a microphone having a lower internal impedance than conventionally obtained.—B.B.B.

2,272,984

5.10 SEISMOGRAPH

Otto F. Ritzmann, assignor to Gulf Research & Development Company.
February 10, 1942, 3 Claims (Cl. 177–352).

Vibration pick-up having a spring-suspended magnetic structure and a spring-suspended voice coil, resonated at

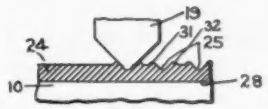


two different frequencies so that the frequency range at which the pick-up is sensitive may be extended. Capacity and piezoelectric embodiments are also described.—B.B.B.

Re 22,183

5.16 APPARATUS FOR RECORDING SOUND ON THIN DISKS

Lincoln Thompson, assignor to The Sound Scriber Corporation. Orig. No. 2,200,866 dated May 14, 1940.
September 22, 1942, 5 Claims (Cl. 274–9).

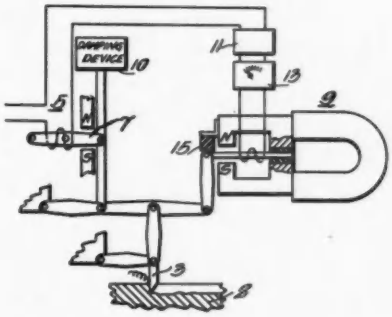


A method of recording sound by embossing the grooves on a disk of very thin material without causing said disk to warp. This is accomplished by dispensing with the usual compliant pad on the turntable.—L.W.S.

2,284,744

5.16 SOUND RECORDING

Edward W. Kellogg, assignor to Radio Corporation of America.
June 2, 1942, 18 Claims (Cl. 179–100.4).

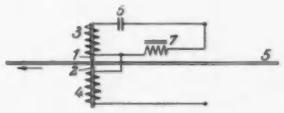


Means of introducing in hill and dale recording a distortion complementary to reproducer tracing distortion by supplying an additional horizontal or vertical displacement proportional to the slope of the normal modulation at that instant.—L.W.S.

2,285,079

5.16 ELECTROMAGNETIC SOUND REPRODUCING DEVICE

Gunther Behre, assignor to C. Lorenz Aktiengesellschaft.
June 2, 1942, 3 Claims (Cl. 179–100.2).

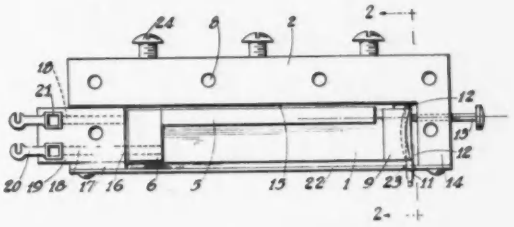


This patent describes means for combining in a magnetic tape reproducer the advantages of unipolar reproduction of low frequencies with bipolar reproductions of high frequencies. In one of the three embodiments described the equivalent of a cross-over network is used to interconnect the two coils of a bipolar reproducer.—L.W.S.

2,286,178

5.16 PHONOGRAPH RECORDER

Otto Kornei, assignor to the Brush Development Company.
June 9, 1942, 13 Claims (Cl. 179–100.41).

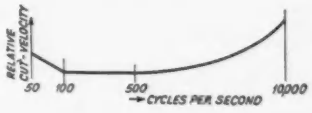


Lateral type phonograph recorder employing a single resonant, well-damped mechanical system of high stiffness whose characteristics are unaffected by the cutting load. Also a stylus holder with low inertia which clamps the stylus in such a manner as to eliminate resonance in the stylus shank within the useful frequency range.—L.W.S.

2,286,494

5.16 SOUND TRANSLATING DEVICE

Roland A. Lynn and Jarrett L. Hathaway, assignors to Radio Corporation of America.
June 16, 1942, 12 Claims (Cl. 179–100.4).

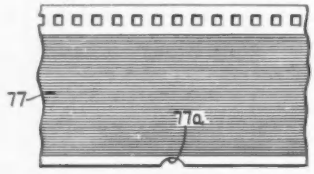


A system of pre- and post-equilization (now commonly known as Orthacoustic Characteristic) used in the recording and reproduction of sound. Also the use of automatic volume control amplifiers in conjunction with sound recording wherein pre-equalization is employed in the volume control circuit.—L.W.S.

2,289,555

5.16 SOUND RECORDING AND REPRODUCING MACHINE

Louis J. Simons, assignor of one-third to Bernard Arbuse, and one-third to Sol P. Schechter.
July 14, 1942, 19 Claims (Cl. 179–100.4).

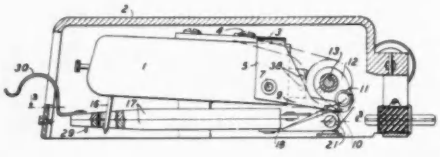


A machine for recording sound by the engraving method on a long, narrow, endless, flexible strip of film. Describes means to prevent convolutions of the film on a spool from binding. Also means for reproducing sound from above described film and for selecting any desired portion thereof. —L.W.S.

2,295,712

5.16 RECORDER-REPRODUCER HEAD

William J. Brown, assignor to Western Electric Company, Inc.
September 15, 1942, 5 Claims (Cl. 274–30).



A method of mounting a recording head in combination with a reproducing head wherein the recording stylus projects through an eyelet in the reproducer, thus allowing instantaneous playback.—L.W.S.

2,296,870

5.16 SOUND RECORDING AND REPRODUCING

Barton A. Proctor and Ferdinand C. W. Thiede, assignors to B. A. Proctor Company, Inc.
September 29, 1942, 30 Claims (Cl. 274–12).

2,296,871

5.16 INDEX MEANS FOR SOUND TRANSLATING

Barton A. Proctor, assignor to B. A. Proctor Company, Inc.
September 29, 1942, 15 Claims (Cl. 274–12).

2,296,872

5.16 SOUND RECORDING AND REPRODUCING APPARATUS

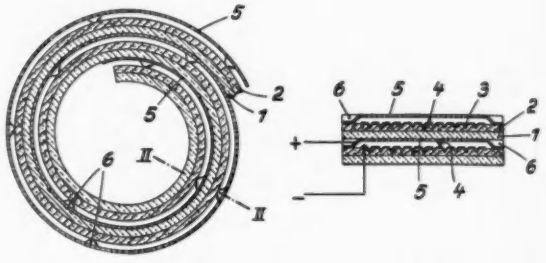
Barton A. Proctor, assignor to B. A. Proctor Company, Inc.
September 29, 1942, 19 Claims (Cl. 274–9).

This and the two preceding patents relate to sound recording by embossing on thin flexible disks at constant groove speed, being intended primarily for use in dictation and transcription of letters, etc. The second patent describes means for indexing the location of material recorded on the disk. The third patent is mainly concerned with an improved method of indicating the position on the disk of the recorder or reproducer. This is accomplished by employing an illuminated indicator which casts a position indicating shadow on the face of the disk.—L.W.S.

2,297,271

5.16 GALVANOPLASTIC MULTIPLICATION OF SOUND RECORD BANDS

Hugo Westerkamp, vested in the Alien Property Custodian.
September 29, 1942, 1 Claim (Cl. 204–5).

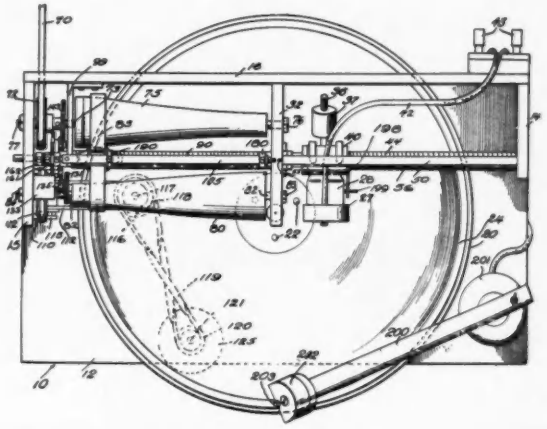


This patent describes a means of producing a matrix of a sound record which is engraved on film strip instead of the usual flat disk; a specially shaped copper anode is spirally wound up with the original strip record.—L.W.S.

2,302,732

5.16 SOUND RECORDING AND REPRODUCING MECHANISM

Charles E. Yetman.
November 24, 1942, 18 Claims (Cl. 74–393).

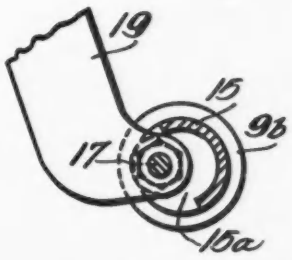


A sound recording and reproducing mechanism which achieves constant linear groove velocity by means of continuously variable cone pulley driving system. There is also a method of keeping the driving system synchronized with the position of the stylus on the disk through interlocking lead screws.—L.W.S.

2,301,616

5.16 PHONOGRAPHIC APPARATUS

Edward C. Conrad, assignor to Radio Corporation of America.
November 10, 1942, 5 Claims (Cl. 274–1).

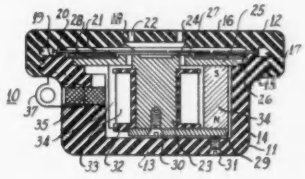


A recording cutter mounting in which adjusting means are provided in the form of eccentrically mounted pivotal bearings.—L.W.S.

2,298,764

5.17 SOUND TRANSLATING DEVICE

Albert F. Horlacher, assignor to Associated Electric Laboratories, Inc.
October 13, 1942, 3 Claims (Cl. 179–114).

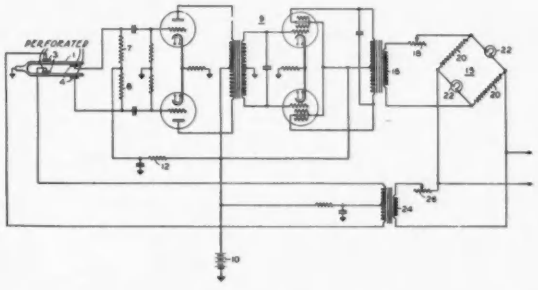


Describes a mechanical structure for a telephone-receiver. The principal features are an annular air gap and the provision of a stack of paper rings for damping of the diaphragm.—B.B.B.

2,302,895

5.19 CONTROL CIRCUIT FOR DRIVING FORKS

Leland B. Root, assignor to Western Union Telegraph Company.
November 24, 1942, 11 Claims (Cl. 250–36).

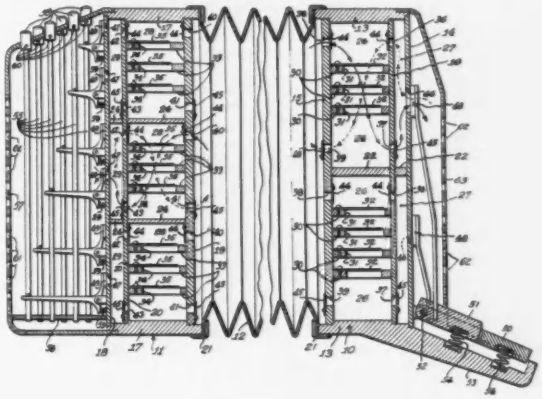


A bridge circuit is employed to keep at a constant predetermined value the current to maintain a tuning fork in vibration. Slight adjustments in frequency are achieved by changing the amplitude of vibration by the aid of resistor **26**. The damping associated with electromagnetic methods of maintaining a fork in vibration is avoided by the use of electrostatic pick-ups and driving electrodes, both suitably polarized, which are perforated to minimize air damping. Note the arrangement of electrodes for proper phasing. Resistors **20** are of low temperature coefficient wire while the other arms of the bridge may be incandescent lamps.—R.W.Y.

2,295,588

6.1 MUSICAL INSTRUMENT

Aldo Logli.
September 15, 1942, 4 Claims (Cl. 84–376).

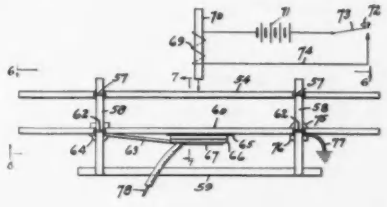


Accordions are commonly furnished with at least two reeds for each tone that is to be produced, one reed for each direction of motion of the bellows. In the arrangement here disclosed the direction of the air flow is rectified by the flap-valves **44** and **45** so that only one reed need be provided for each tone. Conforming to the usual practice, reeds of several pitches may be operated by the opening of a single valve **46**, but it is not apparent how in this construction the reeds of such a set may be controlled separately.—R.W.Y.

2,284,911

6.2 MUSICAL INSTRUMENT

L. A. Maas.
June 2, 1942, 5 Claims (Cl. 177–7).

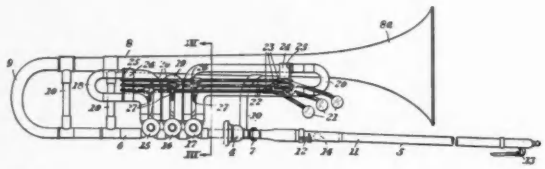


The vibrations of a chime, either bar or tubular, which may be initiated by a striker solenoid **69**, are translated into electrical energy by the aid of an electrostatic pick-up. This consists of a plate insulated from the chime and of a different contour therefrom, which is held lightly in contact by spring **63**. When two chimes are used, as shown in the figure, tuned in unison, the percussive sound of the striking may be minimized.—R.W.Y.

2,288,743

6.3 WIND INSTRUMENT

James H. Reed, III.
July 7, 1942, 4 Claims (Cl. 84–395).

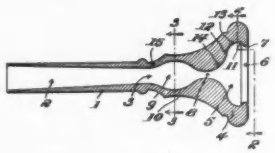


A combination valve and slide trombone is disclosed which makes it possible to change rapidly from one to the other. This is accomplished by having the valve keys carried on hinge rods within reach of the fingers of the right hand when the slide is in the first position. The valve section constitutes a unit which replaces the usual "lower bell branch," and may therefore be installed by a minimum of labor.—R.W.Y.

2,302,492

6.3 MOUTHPIECE FOR MUSICAL BRASS WIND INSTRUMENTS AND THE LIKE

J. W. Dobie, assignor of one-half to F. L. Schweitzer.
November 17, 1942, 6 Claims (Cl. 84–398).

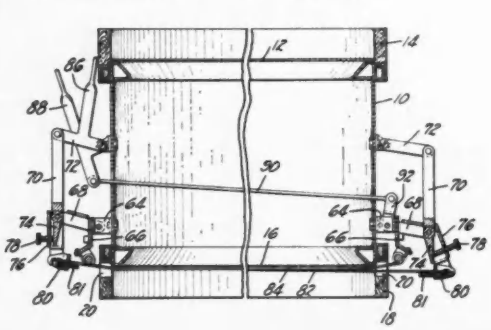


The principal feature of this invention for a brass wind instrument mouthpiece is the inclusion of an expansion 9 between the tone chamber 5 and the stem taper 2. The expansion is intended to improve pitch control during soft playing. It appears that this construction might be difficult to reproduce and gage with current manufacturing methods.—R.W.Y.

2,295,479

6.4 DRUM SNARES

Le Roy J. Jeffries, assignor to C. G. Conn, Ltc.
September 8, 1942, 7 Claims (Cl. 84–415).

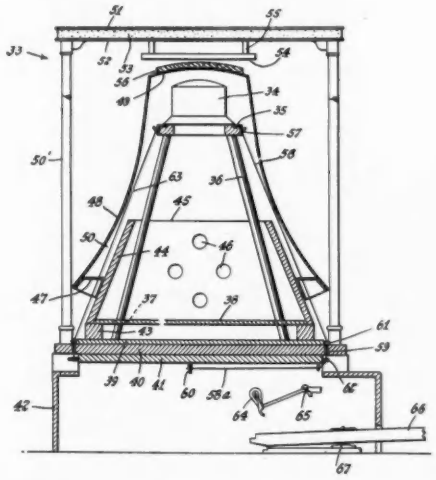


This drum is equipped with two sets of snares, which may be of wire and silk, either or both of which may be used to produce the quality of sound desired at the moment. The snares themselves are alternated so as to bear symmetrically on the drum head.

2,300,012

6.6 MUSICAL INSTRUMENT

Samuel Rubenstein.
October 27, 1942, 6 Claims (Cl. 84–174).

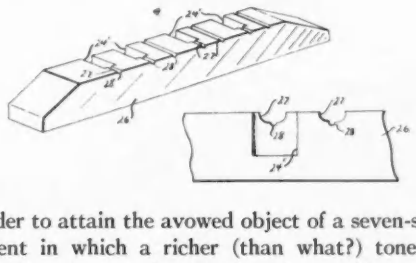


This musical instrument provides for mixing the sound from a loudspeaker **34** and a tuned vibrator as **58a**. In addition to air cavities appropriately connected by holes as **46**, the walls themselves are intended to participate in the vibration. Strings **58** and **63** may be responsive to the sound from the loudspeaker or, "alternatively, the instrument may be operated as a piano with the strings **58, 58a** vibrating and the superposed sound chambers enhancing and enriching the tone."—R.W.Y.

2,292,232

6.7 MUSICAL INSTRUMENT

Emil Liske.
August 4, 1942, 2 Claims (Cl. 84–312).



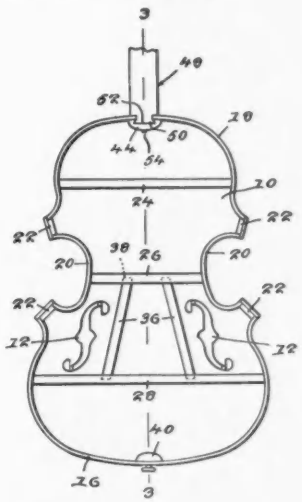
In order to attain the avowed object of a seven-stringed instrument in which a richer (than what?) tone is produced, this guitar is furnished with a bridge whereby longer bearing surfaces are provided for the smaller strings than for the larger ones. One form is illustrated in the adjacent figure wherein the vibrating length of the thicker

strings is increased by cutting out the notches **24′**. Receiving channels **27** guide the string into grooves **28**.—R.W.Y.

2,299,923

6.7 MUSICAL INSTRUMENT

Otis D. Nall.
October 27, 1942, 3 Claims (Cl. 84–267).

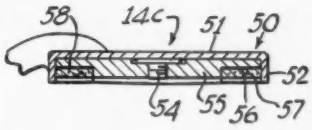


Instead of the usual brace rods, this guitar contains reenforcing "sills," **24, 26, 28, 36,** and a system of pins such as **54**. It is claimed that this construction effects an improvement in durability as well as in tone quality.—R.W.Y.

2,292,767

6.8 RESONATOR PAD FOR MUSICAL INSTRUMENTS

Albert Page.
August 11, 1942, 5 Claims (Cl. 84–385).

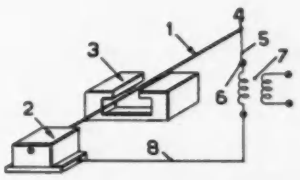


Although this invention is called a resonator pad its announced objects are durability and positive closure. The seal consists of an annular washer **57**, as of leather, attached to the disk **55** and protected by the skirt **52**. Various methods of affixing the disk are shown in the drawings and specifications, but the claims are limited to the screw at the center.—R.W.Y.

2,293,372

6.9 MEANS FOR AMPLIFYING MECHANICAL VIBRATIONS

Serge Vasilach, assignor of three-fourths to Société des Telephones Picart Lebas.
August 18, 1942, 2 Claims (Cl. 84–1.14).

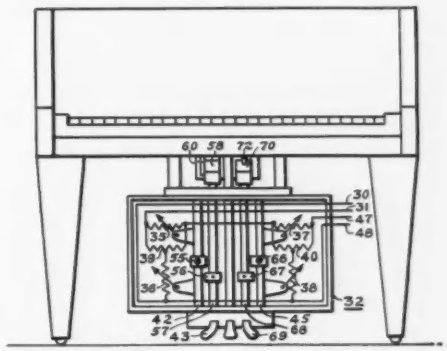


A conductor of electricity is arranged to vibrate in a magnetic field to produce electrical voltages in the well-known manner. Although the specifications include vibrating strings as of pianos and violins, the claims appear to be restricted to the fixed-free bar illustrated in the figure, having a light flexible conductor attached to the tip. The use of a wire stretched through a magnetic field for a burglar alarm is mentioned.—R.W.Y.

2,297,829

6.9 ELECTRONIC PIANO WITH PEDAL CONTROL

J. H. Hammond, Jr.
October 6, 1942, 9 Claims (Cl. 84–1.27).



Pedal-operated attenuators for electronically amplified piano are arranged to become effective after the usual mechanical controls of the "soft" and "loud" pedals have been applied fully, thereby accentuating the musical effects beyond that possible with the mechanical controls alone.—R.W.Y.

2,300,609

6.9 ELECTRIC MUSICAL INSTRUMENT

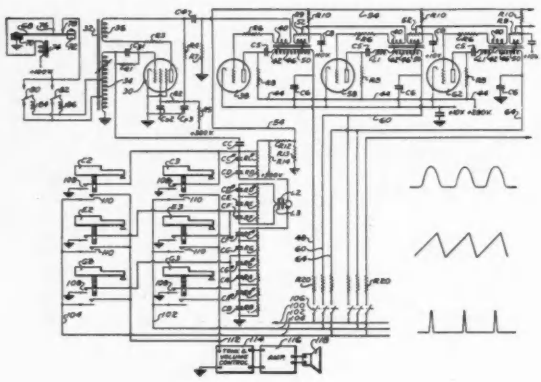
V. I. Zuck, assignor to Everett Piano Company.
November 3, 1942, 3 Claims (Cl. 84–1.09).

According to this disclosure, one may select the relative loudness of a stop of an electric organ, containing vibrating reeds with electrostatic pick-ups, independently of the loudness of another set of reeds being played simultaneously. This is accomplished by providing two or more tablets for each stop, so connected that the polarizing voltage applied to the pick-ups when the *forte* tablet is depressed is about twice that when the *mp* tablet is depressed. Series resistors and shunting capacitors are needed at the switches to suppress undesirable interference in other parts of system.—R.W.Y.

2,301,869

6.9 FREQUENCY GENERATING SYSTEM

Laurens Hammond.
November 10, 1942, 2 Claims (Cl. 250–36).

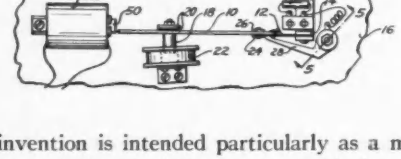


A relaxation oscillator system is disclosed whereby a wave form suitable for musical purposes is produced and by which frequency division is reliable even though the input signal is varied over the range of an octave. The latter is accomplished by controlling the grid bias in line **54** by the operation of the key, such as **G3**, by which the particular frequency is selected. The primary oscillator includes a vibrato circuit. Reflection of the lower frequencies back into the oscillator is minimized by keeping **R9** low compared with the input impedance of the stage following, and thus no buffer stage is necessary.—R.W.Y.

2,301,870

6.9 VIBRATORY REED DRIVE

David Hancock, Jr., assignor to Hammond Instrument Company.
November 10, 1942, 8 Claims (Cl. 172–126).

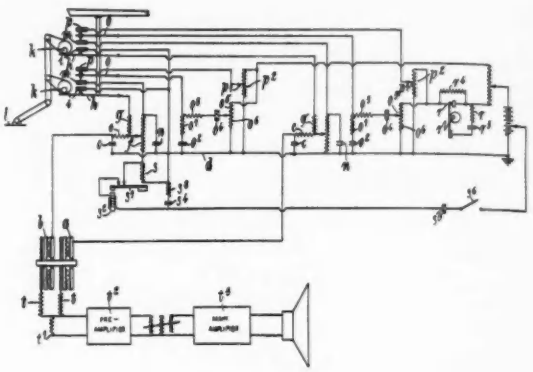


This invention is intended particularly as a means for producing variations in inductance suitable for a vibrato effect circuit, such as shown in the preceding patent. Note the iron dust core **18** vibrating within coil **22**. The contact member **28** moves with the vibrating part **10** in such a manner as to close the circuit to drive coil **52** only while part **10** is rotating clockwise. Observe that coil **52** is displaced relative to the equilibrium position of the vibrator **10**. After the vibrator passes the core of the coil the magnetic field serves to limit the amplitude of motion. Sixty-cycle power may be used to energize the system when it is adjusted to vibrate at its normal rate of seven per second.—R.W.Y.

2,302,457

6.9 ELECTRICAL MUSICAL INSTRUMENT

A. H. Midgley and A. M. Midgley.
November 17, 1942, 3 Claims (Cl. 84–1.26).

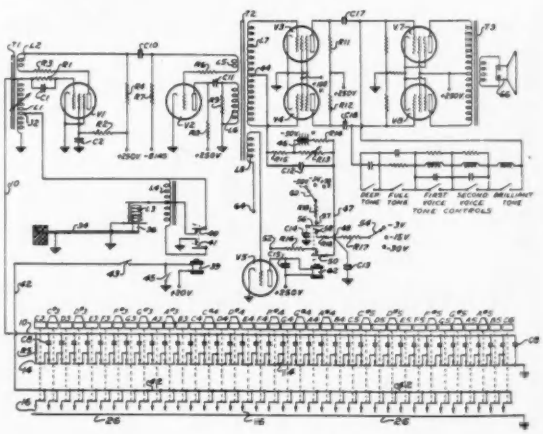


Combinations of resistors and capacitors are provided in the polarizing circuits of electrostatic tone generators whereby the attack and decay of sound produced thereby may be varied at will. Two tremulants are available, the one being motor-driven and consisting of components identified by **r** in the figure, and the other operated by a vibrating reed, indicated at **s**.—R.W.Y.

2,301,871

6.9 ELECTRICAL MUSICAL INSTRUMENT

John M. Hanert, assignor to Hammond Instrument Company.
November 10, 1942, 25 Claims (Cl. 84–1.11).



As a key is depressed on the electrical musical instrument constructed according to this disclosure, the shorting resistor **R5** is disconnected, thereby allowing the oscillator **V1** to operate at a frequency determined by the inductances and the number of capacitors **C8** remaining in the circuit. The presence of a signal in tube **V5** causes the relay **62**

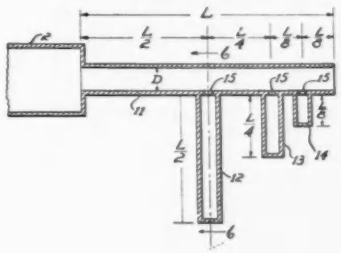
to raise the control grid bias on tubes **V3** and **V4** so as to produce a desired rate of attack. The slight delay in the operation of this relay and associated components prevents any of the transients incident to the start of oscillation from being heard.

Although a slight vibrato may be imparted to the tone at all times by the fluctuating inductance of **L3**, the extent of the vibrato is under the control of the player by a "double touch" system whereby a further depression of a key operates relay **39**. Should two or more keys be depressed simultaneously, the highest of the depressed keys will determine the frequency of the master oscillator.—R.W.Y.

2,297,046

7.7 MEANS OF PREVENTING SHOCK EXCITATION OF ACOUSTIC CONDUITS OR CHAMBERS

Roland B. Bourne, assignor to the Maxim Silencer Company.
September 29, 1942, 34 Claims (Cl. 181–48).



In order to prevent the shock excitation of resonant acoustic conduits or chambers, openings are located at one or more of the pressure antinodes. These openings communicate with the atmosphere or with mechanical oscillators or with resonators tuned to the natural frequency at which the antinode occurs. In most of the claims the conductivity of the opening is limited to the range from 3 percent to 20 percent times $(4S/\pi)^{\frac{1}{2}}$, **S** being the cross-sectional area of the main conduit.—C.E.N.

2,299,157

7.7

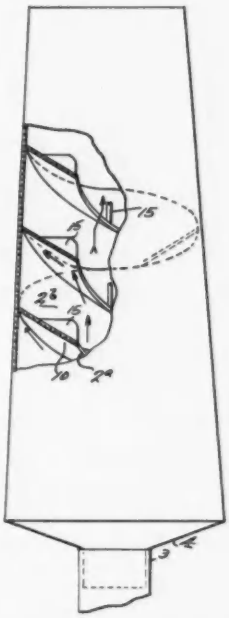
Wilfred W. Lowther, assignor to Donaldson Company, Inc.
October 20, 1942, 3 Claims (Cl. 180–54).

In an automobile, the air intake conduit is located immediately behind the radiator so that intake noise is projected away from the passengers.—C.E.N.

2,300,130

7.7

Howard McCurdy.
October 27, 1942, 6 Claims (Cl. 181–47).

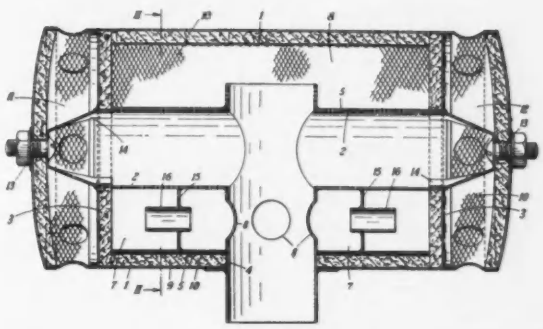


In this silencer a ribbon is formed into a helix between the central passage and the outer shell so that the expanding gas is "sliced off" in its passage through the unit.—C.E.N.

2,297,530

7.7

Joseph George Blanchard, assignor of one-half to Cecil Gordon Vokes.
September 29, 1942, 10 Claims (Cl. 181–59).



An intake silencer for pulsating gases in which the inlet tube and surrounding tubes form crescent-shaped chambers with surrounding tubes. The tubes and chambers may act as tuned or surge chambers.—C.E.N.

Index to Volume 14

How to Use This Index

THIS Index is of similar form to the Cumulative Index of this journal, published in November, 1939, and is composed of two main divisions: The Author Index and the Subject Index.

The Subject Index to Volume 14 of *The Journal of the Acoustical Society of America* lists the titles of all the papers and abstracts under eleven section headings as follows: 1, Acoustical Society of America; 2, Architectural Acoustics; 3, Books and Bibliographies; 4, Ear and Hearing; 5, Applied Acoustics. Instruments and Apparatus; 6, Musical Instruments and Music; 7, Noise; 8, Standards; 9, Speech and Singing; 10, Supersonics; 11, Waves and Vibrations. Each of these sections is further divided into a considerable number of decimally numbered subjects, which are listed below under the heading, "Classification of Subjects." Each subject is divided into four parts entitled Papers, Subtitles, Abstracts, and Patents. Under Papers will be found the original titles of all the papers appearing in the journal on that subject. Under Abstracts are listed the titles of the papers presented at meetings. Since a great amount of valuable material appears in the journal in papers whose titles cannot fully describe all the subjects which the papers cover, some subtitles of papers have been indexed under the heading Subtitles. When subtitles covering the material did not appear in the paper, they were written; the captions of some of the figures were also included under this heading. Thus, while the Subtitles portion of the Index is informal, it is hoped that it will increase the probability of finding the desired information quickly. All patents appearing in the journal are listed under the heading Patents.

References on most subjects can be located immediately by a logical use of the Classification of Subjects below. In case the reference sought is of an unusual character such that there is uncertainty as to the subject under which it might have been classified, this can usually be found quite quickly by the process of eliminating the sections and subjects under which it is quite improbable that it might have been listed. In case of doubt, a title has often been listed under a number of subjects.

Obviously, the Author Index is more convenient than the Subject Index when one knows the name of the author of the paper in which he is interested.

The References to Contemporary Papers on Acoustics are identified in each issue by the same decimal numbers listed below, and may be consulted for references in other journals than our own. In Volume 14 these references will be found on pages 116, 169, 195, and 242.

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PATENT

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2.2 Auditorium Design (see also 7.6)

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Practical acoustics and planning against noise. Hope Bagenal. **14:** 168—1942

PATENTS

Acoustical apparatus. **14:** 121—1942
Acoustical assembly. **14:** 120—1942
Acoustical material. **14:** 121—1942
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2.4 Sound Absorption, Theory and Methods of Measurements (see also 2.5 and 2.7)

PAPER

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ABSTRACT

Notes on acoustic impedance measurement. Hale J. Sabine. **14:** 127—1942

2.7 Reverberation, Theory and Calculation of (see also 2.4, 2.9, and 2.10)

PAPER

Perturbation of sound waves in irregular rooms. R. H. Bolt, H. Feshbach, and A. M. Clogston. **14:** 65—1942

2.9 Sound Transmission, Theory and Methods of Measurement (see also 2.7 and 2.10)

PATENTS

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Sound deadener. **14:** 122—1942

2.11 Vibration Insulating Supports

PATENTS

Antivibration means and method of use of same. **14:** 122—1942
Shockproof isolator. **14:** 122—1942
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4. Ear and Hearing

4.1 General, Unclassified

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ABSTRACT

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ABSTRACT

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4.5 Instruments Relating to Hearing

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PAPER

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4.10 Subjective Tones

PAPER

Experimental study of subjective tones produced within the human ear. Chesney R. Moe. **14**: 159—1942

5. Applied Acoustics. Instruments and Apparatus

5.1 General, Unclassified

PAPERS

Survey on air raid alarm signals. John E. Volkmann and Max L. Graham. **14**: 1—1942

Use of counter circuits in frequency dividers. E. L. Kent. **14**: 175—1943

ABSTRACTS

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Sounding systems for public air raid warning. E. J. Abbott. **14**: 130—1942

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5.3 Acoustical Impedance Measurement (see also 11.4)

PAPER

Notes on acoustic impedance measurement. Hale J. Sabine. **14**: 143—1942

ABSTRACT

Notes on acoustic impedance measurement. Hale J. Sabine. **14**: 127—1942

5.4 Analyzers and Filters. Acoustic Filters. Oscillographs (see also 5.15)

PAPER

Laryngeal ventricle considered as an acoustical filter. Abe Pepinsky. **14**: 32—1942

ABSTRACT

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5.7 Frequency Standards. Frequency Measuring and Recording Instruments

PAPER

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ABSTRACT

Method for measuring the frequency of vibration or rotation. E. L. Kent. **14**: 128—1942

PATENTS

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Three-tone stethoscope. **14**: 123—1942

Tonoscope. **14**: 198—1943

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PAPERS

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Experiments with the noise analysis method of loudspeaker measurement. Benjamin Olney. **14**: 79—1942

Improved low frequency horn. Paul W. Klipsch. **14**: 179—1943

ABSTRACTS

Automatic direct inking audiofrequency response recorder. Benjamin Olney. **14**: 129—1942

Experiments with the noise analysis method of loudspeaker measurement. Benjamin Olney. **14**: 128—1942

New family of horns. Vincent Salmon. **14**: 128—1942

PATENTS

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Electromagnetic transducer. **14**: 199—1943

Fibrous acoustic diaphragm. **14**: 244—1943

Horn. **14**: 123—1942

Loudspeaker. **14**: 199, 245—1943

Pneumatically operated loudspeaker. **14**: 244—1943

Selective electro-acoustical transducer. **14**: 244—1943

Signal translating apparatus. **14**: 245—1943

Sound absorbing apparatus. **14**: 244—1943

Sound reproducing device. **14**: 245—1943

5.9 Microphones, Vibration Microphones, and Microphone Calibration Equipment

PAPER

Absolute pressure generator and its application to the free-field calibration of a microphone. W. Jay Kennedy and C. P. Boner. **14**: 19—1942

PATENTS

Acoustic device. **14**: 201—1943

Electrical device. **14**: 200—1943

Electroacoustical apparatus. **14**: 123, 246—1942

Leakage reducing means. **14**: 201, 245—1943

Microphone. **14**: 246—1943

Piezoelectric device. **14**: 200—1943

Reproduction of sound. **14**: 200—1943

Sound translating device. **14**: 201—1943

Vibration pick-up. **14**: 246—1943

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5.10 Navigational Instruments. Depth and Altitude Finding Instruments. Geophysical Prospecting. Under-Water Sound. Submarine Detectors

PAPER

Under water sound of natural origin. E. O. Hulburt. **14**: 173—1943

PATENTS

Method and apparatus for seismic surveying. **14**: 124—1942

Seismic wave detector. **14**: 123—1942

Seismograph. **14**: 246—1943

5.11 Oscillators

ABSTRACT

Method for changing the frequency of a complex wave. E. L. Kent. **14**: 128—1942

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ABSTRACTS

Automatic direct inking audiofrequency response recorder. Benjamin Olney. **14**: 129—1942

Improvements in the acoustic wattmeter. J. H. Enns and F. A. Firestone. **14**: 129—1942

5.16 Sound Recording and Reproducing (see also 5.13)

PATENTS

Apparatus for recording sound on thin disks. **14**: 247—1943

Electromagnetic sound reproducing device. **14**: 247—1943

Galvanoplastic multiplication of sound record bands. **14**: 248—1943

Index means for sound translating. **14**: 248—1943

Means and method for producing sound effects. **14**: 124—1942

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Phonographic apparatus. **14**: 248—1943

Phonograph recorder. **14**: 247—1943

Recorder-reproducer head. **14**: 248—1943

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Sound recording and reproducing. **14**: 248—1943

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Sound recording and reproducing machine. **14**: 247—1943

Sound recording and reproducing mechanism. **14**: 201, 248—1943

Sound translating device. **14**: 247—1943

Stereophonic sound recording and reproduction. **14**: 124—1942

5.17 Telephone Receivers

PATENT

Sound translating device. **14**: 249—1943

5.19 Tuning Forks

PATENT

Control circuit for driving forks. **14**: 249—1943

6. Musical Instruments and Music

6.1 General, Unclassified

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Acoustics of music. Wilmer T. Bartholomew. **14**: 114—1942

ABSTRACT

Pitch scales. Don Lewis. **14**: 127—1942

PATENT

Musical instrument. **14**: 249—1943

6.2 Bells

PATENT

Musical instrument. **14**: 249—1943

6.3 Brass

PAPER

Experimental study of trumpet embouchure. Hayward W. Henderson. **14**: 58—1942

ABSTRACT

Experimental study of trumpet embouchure. Hayward W. Henderson. **14**: 127—1942

PATENTS

Mouthpiece for musical brass wind instruments and the like. **14**: 250—1943

Pitch modifying mouthpiece for brass wind musical instruments. **14**: 125—1942

Wind musical instrument. **14**: 201—1943

Wind instrument. **14**: 250—1943

6.4 Drums and Traps

PATENTS

Drum snares. **14**: 250—1943

Drum vitalizer. **14**: 202—1943

Percussion musical instrument. **14**: 125—1942

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6.5 Organs (see also 6.9)

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Comparison between a Haskell organ pipe and a simple open pipe. R. C. Biner and A. S. Hall. **14**: 140—1942

Edge tones. Arthur Tabor Jones. **14**: 131—1942

ABSTRACT

Edge tones with turbulent air sheets. A. T. Jones. **14**: 127—1942

PATENT

Electric organ. **14**: 125—1942

6.6 Pianos

PATENTS

Musical instrument. **14**: 250—1943

Piano. **14**: 202—1943

Piano string support. **14**: 202—1943

6.7 Violin Family

PATENTS

Musical instrument. **14**: 250, 251—1943

6.8 Wood Winds

PAPER

Experimental study of the tone quality of the Boehm clarinet. C. S. McGinnis, H. Hawkins, and N. Sher. **14**: 228—1943

PATENTS

Reed. **14:** 202—1943

Reed of cane, plastic, or any other material for clarinets, saxophones, and like musical instruments. **14:** 202—1943

Resonator pad for musical instruments. **14:** 251—1943

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ABSTRACT

Method for changing the frequency of a complex wave. E. L. Kent. **14:** 128—1942

PATENTS

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7.3 Audiograms of Noise

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7.4 City Noise

PAPER

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Transmission of sound signals in congested city areas. Joseph B. Kelly. **14:** 129—1942

7.7 Machinery Noise

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Sound attenuating device. **14:** 125—1942

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8.1 General, Unclassified

PAPERS

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9.1 General, Unclassified

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PAPER

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10.5 Liquids, Supersonic Velocities, Dispersion, and Absorption

ABSTRACT

Supersonic transmission at oblique incidence through a solid plate in water. J. B. Smyth and R. B. Lindsay. **14:** 127—1942

10.6 Solids, Supersonic Velocities, Dispersion, and Absorption

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PATENTS

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